SYNTHESES AND THERMAL REARRANGEMENTS OF FLUORINATED BICYCLO[2.1.0]PENTANES

By

DHEYA MORTADA AL-FEKRI

A DISSERTATION PRESENTED TO THE GRADUATE SCHOOL
OF THE UNIVERSITY OF FLORIDA IN
PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

UNIVERSITY OF FLORIDA

1985

To my parents
MORTADA and ZEHRA AL-FEKRI
without whom this would not have been possible.

ACKNOWLEDGEMENTS

I am greatly indebted to Professor William R. Dolbier, Jr., for his unique leadership, plentiful suggestions, enthusiasm, and patience during the course of this work. His great concern and support have made him a special friend. It has been a pleasure to be a part of his research team.

Thanks are due to Dr. Conrad Burkholder, Dr. Simon Sellers, Dr. Seth Elsheimer, and Gene Wicks for their helpful instruction and discussions. Thanks go to Jim Rocca and Paul Kenya for running the high field NMR spectra.

Finally, I would like to express my deepest appreciation to Sandy Roberts and Patricia Carlton, who offered moral support and encouragement.

TABLE OF CONTENTS

		Page
ACKNOWELDGEMENTS		iii
ABSTRACT		vi
CHAPTER		
1	GENERAL INTRODUCTION	1
	Fluorine as a Substituent	1
	Bicyclo[2.1.0]pentane	14
	General	14
	Pyrazolines	23
	General	23
	Reaction of Fluorinated Alkenes With 1,3-dipoles and Nucleophiles	28
2	THERMOLYSIS OF 6,6,7,7-TETRAFLUORO-2,3-DIAZA-BICYCLO[3.2.0]HEX-2-ENE	33
	Introduction	33
	Results and Discussion	35
	Photolytic Synthesis of 2,2,3,3-Tetrafluoro-bicyclo[2.1.0]pentane	40
	Thermal Rearrangement of 2,2,3,3-Tetrafluoro-bicyclo[2.1.0]pentane	41
3	SYNTHESIS AND THERMAL REARRANGEMENT OF 6,6-AND 7,7-DIFLUORO-2,3-DIAZABICYCLO[3.2.0]HEPT-2-ENES. ATTEMPTED SYNTHESIS OF 2,2-DIFLUORO-BICYCLO[2.1.0]PENTANE	67
	Synthesis of 3,3-Difluorocyclobutene	67
	Results and Discussion	67
	Synthesis of 6,6- and 7,7-difluorodiaza-bicyclo[3.2.0]hept-2-enes	75
	Results and Discussion	76
	Thermolysis of 6,6- and 7,7-difluoro-bicyclo[3.2.0]hept-2-enes. Attempted synthesis of 2,2-difluorobicyclo[2.1.0]pentant: Results and Discussion	83

4 THERMODYNAMIC EFFECT OF FLUORINE ON CYCLOBUTENE BUTADIENE EQUILIBRIUM ---------- 93

Introduction ---------- 93
Results and Discussion ---------- 96

5 EXPERIMENTAL ---------- 106

Introduction---------- 106

6 GENERAL CONCLUSIONS ---------- 133

APPENDICES

A CALCULATED HEAT OF FORMATION OF TETRAFLUORO-CYCLOBUTANE ---------- 134

B KINETIC DATA ---------- 137

C SELECTED SPECTRA ---------- 159

REFERENCES ---------- 203

BIOGRAPHICAL SKETCH ---------- 211

Abstract of Dissertation Presented to the Graduate School
of the University of Florida in Partial Fulfillment of
the Requirements for the Degree of Doctor of Philosophy

SYNTHESIS AND THERMAL REARRANGEMENTS OF FLUORINATED BICYCLO[2.1.0]PENTANES

By

DHEYA MORTADA AL-FEKRI

MAY 1985

Chairman: William R. Dolbier, Jr.
Major Department: Chemistry

The gas phase thermal rearrangement of 2,2,3,3-tetrafluorobicyclo[2.1.0]pentane (107) to 3,3,4,4-tetrafluorocyclopentene (108) at 334°C-364°C required an activation energy (Ea) of 54.2±1.1 kcal/mol. Mechanistically, this rearrangement is slower than the analogous are for the unfluorinated bicyclopentane (50) by 7.6 kcal/mol. Thermolysis of the 4-methyl derivative (119) of pyrazoline 106 at 382°C gave the exo- and endo-5-methyl derivatives of 107 (120 and 121 respectively). Thermal interconversion of 120 and 121 in the gas phase at 209.0°C-243.0°C required an activation energy of 39.4±0.8 kcal/mol. This energy, which corresponds to C_1-C_4 bond strength in 107, is comparable to the unfluorinated analog and indicates that the increment in Ea (7.6 kcal/mol) for 107 rearrangement must derive from an inhibition of the 1,2-hydrogen shift process of the intermediate

4,4,5,5-tetrafluorocyclopentane-1,3-diyl species (116) as a second step leading to cyclopentene 108.

Addition of diazomethane to 3,3-difluorocyclobutene (139) gave two isomeric pyrazolines 159 and 160 in relative yield ratio of 159/160=2.4. Thermolysis of these pyrazolines at 350°C or 288°C gave nine isomeric products, 161-169. The desired compound 2,2-difluorobicyclo[2.1.0]pentane (131) was not observed. This result can indicate the instability of the difluorobicyclopentane (131) relative to tetrafluorobicyclopentane (107).

Both 3,3-difluorocyclobutene (139) and 3,3,4,4-tetrafluorocyclobutene (45) ring open in a conrotatory fashion to the corresponding 1,3-diene with an equilibrium constant of 945 (at 237°C) and 77.5 (at 315°C) respectively. However, under gas phase conditions, 1-methyl-3,3,4,4-tetrafluorocyclobutene (110) ring opens to its corresponding 1,3-butadiene (111) much more slowly than 139 or 45. This result shows the destabilizing effect of vicinal methyl and fluorine substituents in the diene.

CHAPTER 1
GENERAL INTRODUCTION

Fluorine as a Substituent

The unique properties of fluorine as a substituent derive largely from its high electronegativity, its three nonbonded electron pairs, and its small size. Being a second period element, its orbital dimensions are such that excellent overlap is possible, both in forming σ-bonds and in π-conjugative interactions with contiguous carbon π-systems.[1a,b]

The presence of three nonbonded pairs of electrons on a fluorine, make it a potential π-donating substituent. This property is nicely illustrated by the observation that fluorine directly bonded to a carbocation center stabilizes the carbonium ion,[1c] 1 and 2.

1 2

In spite of its electron withdrawing inductive effect, fluorine actually activates the para position in the chlorination of fluorobenzene.[1c]

The high electronegativity and effective orbital overlap combine to give a very polar, very short C-F σ-bond (1,317 Å relative to 1.766 Å for a C-Cl bond). The thermodynamic effect of fluorine as a substituent is illustrated in the following example[2] (equation (1-1)).

(1-1)

3 4

a , R = H, ΔH = 8 kcal/mol

b , R = F, ΔH = -12 kcal/mol

This effect has been rationalized as being a consequence of fluorine's high electronegativity, which should give rise to strong bonds with less electronegative carbon orbitals, and fluorine's apparent ability to denote electrons to a conjugated π-system, which would give rise to a repulsive antibonding interaction of fluorine's lone pairs with the π-system.[1b,2]

Geminal Fluorine Effect on Cyclopropane Ring

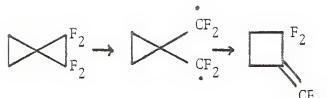
The geminal fluorine effect was first studied extensively by Dolbier[3] who showed quantitatively that the activation energy (Ea), for the isomerization of 1,1-difluoro-2,3-dimethylcyclopropane (5), is 9.4 kcal/mol lower than that for the unfluorinated analog (equation (1-2)).

5 6 (1-2)

This effect was rationalized in agreement with Hoffman's[4] predicition, to be indicative of a specific weakening of the opposite C_2-C_3 bond and was thought to be due to the general increase of strain[5] (ground state effect) in the cyclopropane ring due to the geminal fluorines.

Di-Geminal Fluorine Effect on Cyclopropane Ring

A suitable system which was able to determine the effect of four fluorine atoms on cyclopropane was 1,1,2,2-tetrafluorospiropentane[6] (1) (equation (1-3)).



(1-3)

7 8 9

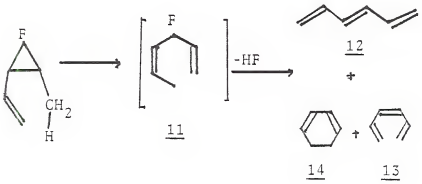
$E_{a,7-9} = 45.4$ kcal/mol

Comparing the Ea of the tetrafluorospiropentane with the Ea of the difluorospiropentane[3] (58.0 kcal/mol) leaves no doubt that the presence of two pairs of geminal fluorines in a cyclopropane ring gives rise to a substantial weakening of that adjacent bond between them.

Mono-Fluorine Substituent Effect on Cyclopropane Ring

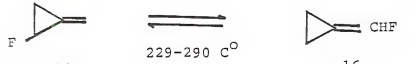
In the contrast to the considerable understanding about gem-difluoro system, very little is known about monofluorocyclopropanes. Very recently Dolbier and Elsheimer[7] found that one fluorine on cyclopropane ring (10) (equation (1-4)) lowers the Ea for the homodienyl shift by 3.3 kcal/mol

relative to the hydrocarbon analog. This can be compared with an additional 4.3 kcal/mol lowering of a gem-difluoro group at 166.2°C (table 1-1).



(1-4)

Another example is the equilibrium system below, equation (1-5), which indicates there is no dramatic thermodynamic effect due to the fluorine substituent being on a



15 16 (1-5)

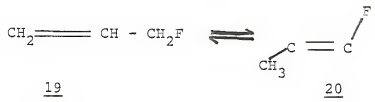
ΔH = - 2.6 kcal/mol

ΔS = 1.0 e.u.

Table 1-1. Activation Parameters for 10, 17, and 18

	E_a kcal/mol	Log A	T_1 °C	$\Delta H^{\neq}$ kcal/mol	$\Delta S^{\neq}$ cal/mol·K	$\Delta G^{\neq}$(166.2°C) kcal/mol	K_{rel} at (166.2°C)
17	30.9±0.4	10.9±0.2	166.2-222.1	29.9	-11.7	35.0	(1)
10	27.6±1.2	10.3±0.6	152.8-171.4	26.7	-14.4	33.0	11.2
10 18	23.3±0.5	10.3±0.3	52.6-86.9	22.7	-13.5	28.6	1540

cyclopropane ring since the above thermodynamic results resemble those for the analogous simple allylic-vinylic isomerization[8] (equation (1-6)).



19 20 (1-6)

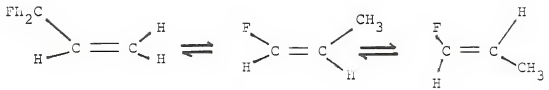
$\Delta H = -2.7$ kcal/mol

$\Delta S = 1.7$ e.u.

Using group equivalent values[8] to determine heat of formation of each of 19 and 20, the author estimated a 2 kcal/mol excess strain energy in 19 due to the fluorine substituent.

Fluorine Effect on Alkenes

It has been shown that a single fluorine on an olefinic unconjugated bond is thermodynamically favored by 3 kcal/mol as first illustrated by Abell[9] and reexamined by Dolbier[8] (equation (1-7)).



21 22 23

	ΔH kcal/mol
21 → 22	- 3.34
21 → 23	- 2.68
22 → 23	+ 0.64

This effect of vinylic fluorine is very similar to a methyl in its ability to stabilize a double bond.[10] The increased thermodynamic stability of monofluorolefins could be explained by the resonance contribution depicted in 24 and 25 in which the non-bonding electrons of fluorine

24 25

back-bond into the C-C π-bond.[11]

Concerning a gem-difluoro substitution on a C=C bond, it seems from the Cope rearrangement of 26 to 27 (equation (1-8))[8] that there is a driving force to convert vinylic CF_2

26 27 (1-8)

E_a = 33.0 kcal/mol

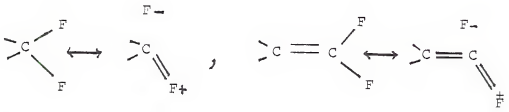
ΔH^* = 5.1 kcal/mol

to allylic or alkyl due to the greater stability of the latter two groups and destabilization of the gem-difluoro olefins, since gem-difluoro substituents on a C=C bond is also thermodynamically destabilizing when one compares the higher heat of hydrgenation of the gem-difluoro-ethylene to that of ethylene[12] (equations (1-9) and (1-10)).

	ΔH kcal/mol	
$CH_2{=}CH_2 + H_2 \rightarrow CH_3CH_3$	-32.6 ± 0.3	(1-9)
$CH_2{=}CF_2 + H_2 \rightarrow CH_3CHF_2$	-38.8 ± 0.8	(1-10)

*This is ΔG, since ΔS assumed equal to zero.

The difference in vinylic and alkyl stabilization by F-substituents has been rationalized by a double-bond, no-bond resonance model.[13]



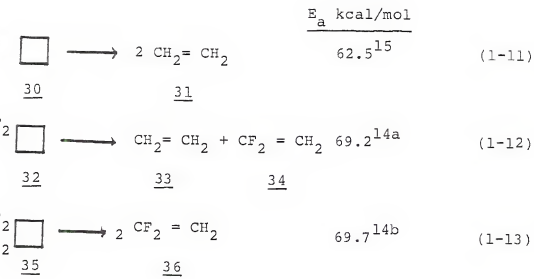
28 28 a 29 29 a

A resonance contributor such as 28a, which has no analogous contributing structure in the monofluorosystem (equation (1-7)), should afford more stabilization to 28 than 29a to the vinylic system 29.*

Fluorine Effect on Cyclobutane Ring

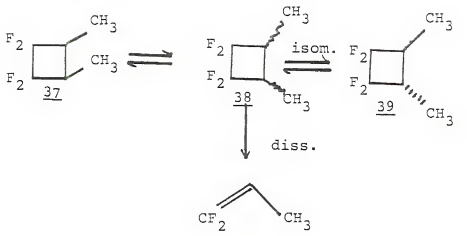
In 1980 Frey[14] examined the thermal fragmentation reactions of 1,1-difluorocyclobutane (32) and 1,1,2,2-tetrafluorocyclobutane (35), demonstrating that these fragmentations were significantly inhibited by the presence of the fluorine substituents (equations (1-11), (1-12) and (1-13)).

*It may be helpful to recognize that the bonded portions of 28a and 29a are isolectronic with a ketone and a ketene respectively.



The fluorine effects on both isomerization* and dissociation* modes of cis-, trans-1,2-dimethyl-3,3,4,4-tetrafluorocyclobutane[16] indicated that β-fluoro substituents have no effect on carbon(1)-carbon(2) stability (equation (1-14)).

*Isomerization was defined as the Ea required to break the first bond C_1-C_2, and dissociation is the Ea required to break the second bond, C_3-C_4.



(1-14)

E_a isom. = 59.8 kcal/mol
(60.1)*

E_a diss. = 62.9 kcal/mol
(60.4)*

However the effect of α-substituents is significant as shown by the increase in Ea for dissociation of all the cyclobutanes with tetrafluoro-substituents over the Ea's for isomerization of the cis- and trans- dimethyl cyclobutanes. Thus, gem-difluoro substituents increase the

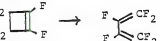
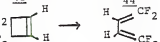
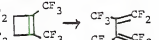
* Numbers in parantheses are the corresponding Ea for the unfluorinated analog in kcal/mol.

strength of σ carbon-carbon bond toward thermolysis causing isomerization to occur at a faster rate than dissociation. It is also well known that perfluorocyclobutane is very much stabilized to fragmentation[17] (Ea=74.2 kcal/mol) and as seen above in the difluoro- and tetrafluoro cases, fluorine substitution definitely stabilizes the cyclobutane ring to overall fragmentation.

Fluorine Thermodynamic Effect on Cyclobutene Ring

A large number of simple cyclobutenes undergo thermal isomerization to dienes by simple unimolecular transformations.[18] These are essentially irreversible with the equilibrium lying well on the side of the diene. Like cyclobutene, perfluorocyclobutene also undergoes a thermal unimolecular isomerization to the diene, but in this case the equilibrium is well over on the side of the cyclic isomer.[19] However, replacing the fluorines in the first and second position with protons again shifts the equilibrium back to the butadiene (table 1-2). Perfluoro-1,2-dimethylcyclobutene[20] isomerizes to an equilibrium mixture containing about 10% of the cyclic compound with a rate constant fairly close to that for perfluorocyclobutene. Thus there is a remarkable fluorine effect on the cyclobutene-butadiene equilibrium in going from a butadiene with three fluorosubstituents on a double bond to butadiene with geminal fluorosubstitution on a double bond. These results were merely rationalized as being due to the destabilizing effect of three fluorine atoms on a double bond.[19]

Table 1-2. Activation Energies and Reaction Enthalpies for Isomerization of Cyclobutenes.

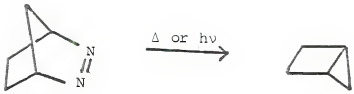
Reaction	E_a[a]	ΔH°[a]	Relative k, at 600K	Ref.
41 → 42	32.9	-8	5×10^4	18
 43 → 44	47.1	+11.7	2.2	19
 45 → 46	47.9	-3	1.0	18d
 47 → 48	46.0	+0.4	1.8	20

a. In kcal/mol.

Bicyclo[2.1.0]Pentane

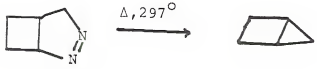
General

The first synthesis of bicyclo[2.1.0]pentane (50) was reported by Criegee and Rimmelin[21] via the azo compound (49) (equation (1-15)). Besides the thermal method, 49 may also be converted to the bicyclopentane via photolysis. However, a considerable amount of cyclopentene is also formed under these conditions. A number of other methods for preparation of 50 and its derivatives have been reported[22] with an



49 50 (1-15)

indication of its chemical behavior as well.[23] Among these methods is the deazetation of pyrazoline 51 (equation (1-16)), a method which has been used generally for cyclopropanation reactions thermally[24] and photochemically.[25]

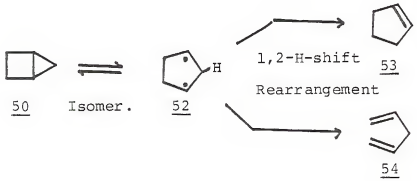


51 50 (1-16)

Bicyclo[2.1.0]pentane undergoes thermal rearrangement* to cyclopentene at around 300°C. The kinetics of the reaction have geen studied independently by Steel[26a] and Chesick.[26b]

*Refers to formation of cyclopentene resulted from a 1,2-hydrogen shift of the incipient 1,3-diyl radical 52, equation 1-17.

The latter found that the Ea for the bicyclopentane rearrangement to cyclopentene, equation (1-17), was 46.6 kcal/mol and a log A of 14.58. This energy corresponds to rapture of C_1-C_4 and the subsequent 1,2-hydrogen shift to give cyclopentene 53.



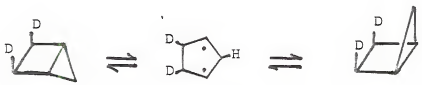
(1-17)

$$E_{a,50 - 53} = 46.6 \text{ kcal/mol}$$

$$E_{a,50 - 54} = 52.5 \text{ kcal/mol}$$

Probably of more importance is the observation that cis- and trans-1-methyl-, 2-methyl- and 5-methylbicyclo[2.1.0]-pentanes undergo thermal isomerization* (equation (1-18) more rapidly than rearrangement to the cyclopentene which is also depicted by the parent 2,3-dideuterobicyclo 2.1.0 - pentane[27a](55) as in table 1-3. The Ea for this process reflects the energy required to break the central bond, C_1-C_4 (equation (1-18)). It was proposed that the

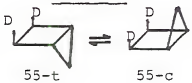
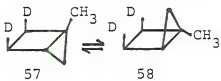
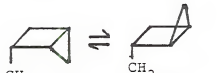
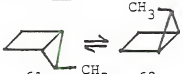
*Refers to the flip-flop of the cyclopropane ring in 55 or 50.



55-t 56 55-c (1-18)

geometrical isomerization and rearrangement proceeded via a common intermediate, a 1,3-diradical (52) (equation (1-17)),

Table 1-3. Activation Parameters and Relative Rate Constant for Isomerization of Bicyclo[2.1.0]Pentanes.

Reaction	E_a kcal/mol	log A	Relative k, at 175°C
 55-t 55-c	37.8±0.1	13.9	1
 57 58	38.0±0.4	14.7	5
 59 60	38.65	13.9	0.3
 61 62	39.1±0.1	14.6	1

This observation is similar to that for the cyclopropane-1,2-d_2 where the Ea for thermal cis-, trans- isomerization is less than that for the rearrangement to propylene.[28] Table 1-3, shows that substitution on positions 1-, 2-, or 5- in bicyclopentane does not seem to have any remarkable effect on the stability of the diradical 52.[27a] An energy diagram for those processes is indicated in figure 1-1.[27b]

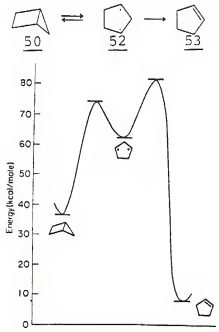


Figure 1-1. Energy Diagram for Thermal Rearrangement of bicyclo[2.1.0]pentane (50), ref. 27b.

1,3-cyclopentadiyl Radical (Closs's Diradical) and Substituent Effects

The proposed intermediate diradical (52) during both isomerization and rearrangement of bicyclo[2.1.0]pentane represents and example of 1,3-cyclopentadiyl radical. It has been detected directly by Buchwalter and Closs[29] who found that ultraviolet irradiation of matrix-isolated (49) at 5.5 K yielded a well-defined electron spin resonance (ESR) spectrum. From the fact that this spectrum was still observed down to 1.3 K and from preliminary CIDNP results, they concluded that the 1,3-cyclopendadiyl diradical had a triplet ground state. Further analysis of the decay kinetics of this species suggested the schematic potential energy surface in figure 1-2 which indicates that the triplet state (T) of the diradical was a minimum on its pentential surface, while the lowest singlet state (S) represents a transition state between the cis and trans bicyclopentane (55-t, 55-c). Their results also enabled them to compute the barrier height between (T) and (S) states as indicated in table 1-4.

Researchers[30] in this area appear to correlate the substituent effects in the isomerization of bicyclopentane with stabilizing and destabilizing effects on the incipient 1,3-cyclopentadiyl radical. An extensive substituent effect study regarding the rearrangement process has not appeared in the chemical literature. However, several C(5) substituted

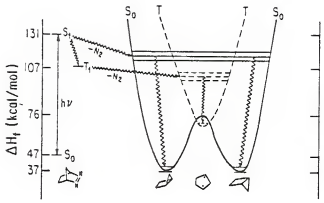


Figure 1-2. Energy Diagram of 50 and 52. The Curvatures of the Potential Curves are Schematic (ref. 29).

Table 1-4. Activation and Tunneling Parameters Used to Compute the Curve Shown in Figure 1-2 (ref. 29).

preexponential factor	A	$10^8 s^{-1}$
barrier height	E	1.6×10^{-13} erg (2.3 kcal/mol)
barrier width	2a	0.64×10^{-8} cm
mass of tunneling particle	m	2.324×10^{-23} g (14 mass unit)

system have been investigated[30] and showed that π-donors at C(5), such as alkoxy, facilitate the isomerization dramatically, but neither a σ-donor such as methyl nor π-acceptor such as methoxycarbonyl and cyano have much influence on the barriers of the isomerization (table 1-5).

Table 1-5. Comparison of Rates and Activation Parameters for the Isomerization of exo-5-substituted Bicyclo[2.1.0]-pentanes.

X	$10^7 k^{150°C}, s^{-1}$	$\Delta G^{\neq}(150°C)$ kcal/mol	$\Delta H^{\neq}$ kcal/mol	$\Delta S^{\neq}$ eu
-CN	5.01	37.2±1.1	41.5±0.8	10.1±0.8
$-CO_2CH_3$	6.24	37.1±3.1	38.5±1.8	3.4±3.1
-H[a]	8.56	36.8	37.7±0.8	2.2
exo-CO_2Et-5-CH_3[b]	131.00	34.6±4.4	35.8±2.2	2.9±5.2
exo-$COCH_3$-5-CH_3[b]	59.39	35.2±1.7	33.9±0.9	-3.0±2.0
-OTs	1790.00	32.2	30.0	-5.2
-OPNB	52900.00	29.5	28.6	-2.1

[a] This reaction was run in gas phase and involved 2-methyl-bicyclo[2.1.0]pentane.
[b] This is a 5,5-disubstituted compound.

When a cyclopropane ring is fused at C(5) of bicyclopentane a dramatic lowering of the Ea for the isomerization was observed[31] (equation (1-19)). This is due to incremental

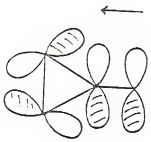
63 64

E_a = 29 kcal/mol (1-19)

strain of cyclopropane ring of 6-8 kcal/mol.[3] However, Baldwin[27a] suggested the stabilization of the 1,3-diradical by the cyclopropane ring lying parallel to the diradical orbitals, is responsible for the activation lowering observed.

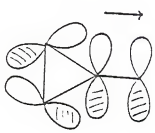
Theoretical[32a,b] models for substituent effects account for half of the experimental reality, the rate enhancin effect of π-donor at C(5) [electron-supplying π-donors substituents, OR,NR_2, should weaken the cyclopropyl bond (antibonding interaction) remote from the substituent by a resonance effect involving electron supply into ψ_4 (65), cyclopropane Walsh orbital].

π-DONOR



65, ψ_4

π-ACCEPTOR



66, ψ_3

They do not accommodate the insensitivity of isomerization (stereomutation) rates to π-acceptors (table 1-5) as they were expected to be; substituents capable of electron withdrawal by resonance, CO_2R, CN, should strengthen the same bond by diminishing an antibonding interaction in ψ_3 (66).

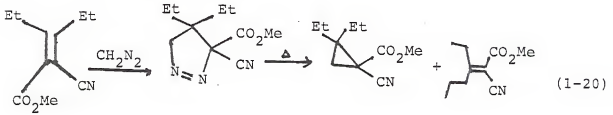
Moreover, not until recently, were Clark et al.[32c] able to discern the differences of effects between σ-, π-donor-acceptors as substituents that result in weakening of

C_1-C_2 bonds and, σ-acceptors as substituents that result in weakening C_2-C_3 opposite bond. The author concluded that fluorine substituent does not act as a pi-donor as originally assumed by Hoffman[32a,b] but predominantly as a sigma-acceptor.

Pyrazolines

General

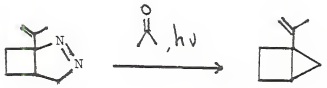
The oldest and most convenient method of pyrazoline synthesis is 1,3-dipolar cycloaddition of diazo compound to an olefin.[33] Because only activated olefins succeeded in this reaction[34] the first pyrazolines which were thermolyzed possessed electron-withdrawing groups on the α- carbon, (equation (-120). Decomposition of pyrazolines



(1-20)

67 68 69 70

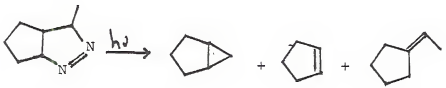
is important from both synthetic and mechanistic[33] viewpoints. Although thermolysis of these compounds can be used to prepare cyclopropanes[35] photolysis[36] is superior for this purpose (equation (1-21)).



(1-21)

71 72

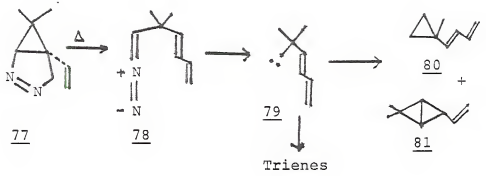
The extent to which diazo compounds play a role in pyrazoline decomposition depends not only on substituents but also on fused ring size and whether thermolysis or photolysis is employed.[37] Whereas 71 gave exclusively 72, a cyclopropane product on photolysis, 73 gave up to 17% of olefinic products 75, 76[25,38] (equation (1-22)).



(1-22)

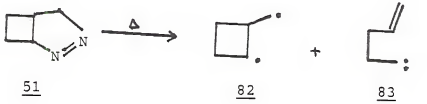
73 74 75 76

Decreasing the size of the fused ring to three carbons led to a new reaction: cycloreversion to an olefinic diazo compound[39] (78) (equation (1-23)).



(1-23)

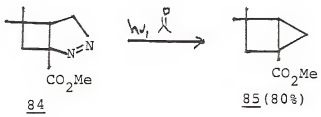
Decomposition of pyrazolines with a four-membered ring (51) occurs via both the carbene and diradical pathways[40] (equation (1-24)). It is believed that higher temperatures



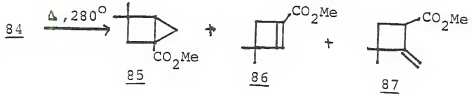
(1-24)

favor a diradical route to the carbene,[33] by passing the azoalkane, and the relatively large amounts of olefins indicate competitive pathways involving a 1,3-biradical species formed by deazetation of azo compounds. Again the relative product yields are noticeably temperature-dependent as would be expected if the vibrationally excited

carbenes are among the intermediates.[40,41] Whereas thermolysis almost always gives olefinic compounds in competitive reactions, photolysis of analogues of diazabicyclics provides a generally useful entry to the cyclopropanes series, especially if sensitizers are used,[41,42] (equations (1-25) and (1-26)).



84 85 (80%) (1-25)

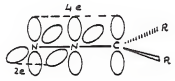


85 86 87 (1-26)

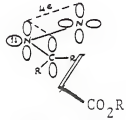
Probably in these reactions the low energy triplet species and the ability of the intermediates and products to dissipate vibrational energy facilitates the product specificities observed.

Diazoalkanes

All 1,3-dipoles are isoelectronic with ozone or nitrous oxide and have a four π-electron system (88) composed of three atomic p-orbitals analogous to the allyl anion, and with an orthogonal double bond not participating in this system as indicated in structure 88, representing diazomethane.[43a]

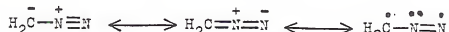


88



89 , T.S.

The most commonly considered resonance forms are presented below along with the less commonly considered singlet biradical resonance form.[43b]

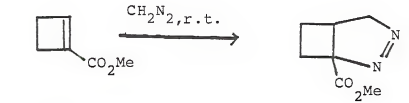


90 91 92

Although non concerted cases have been hypothesized occasionally,[44] 1,3-dipoles generally give concerted cycloaddition reaction.[45]

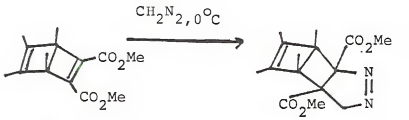
Reaction of Fluorinated Alkenes with 1,3-Dipoles and Nucleophiles

Let us consider diazomethane as the typical example of 1,3-dipoles. The literature on reactions that involve additions of diazomethane to alkene derivatives is concerned mainly with systems that have one or more electron-withdrawing groups attached to the double bond[46] (equations (-27), (1-28)) although additions to but-2-ene have been described.[47a]



Ref. 47b (1-27)

93 94

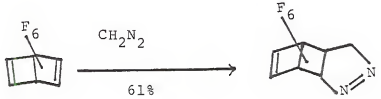


Ref. 47c (1-28)

95 96

The addition of 1,3-dipoles to double bonds is particularly easy with small-ring cyclo-olefins, an effect long attributed to angular strain,[48] but is particularly difficult with fluoro-olefins. Thus diazoalkanes are relatively unreactive

in 1,3-dipolar cycloadditions with alkenes containing vinylic fluorine.[49] Due to its unusually high strain, hexafluorobicyclo[2.2.0]hex-2,5-diene (97) has been found by Barlaw[50] et al. to be a reactive dipolarophile, forming with diazomethane 1:1 adduct rapidly in the dark at (-45°C) in 61% yield (equation (1-29)).



(1-29)

97 98

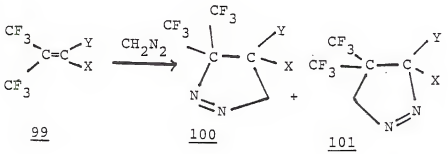
A qualitative reactivity order has been established for olefins, fluoroolefins and fluoralkylolefins towards addition of CH_3CHN_2 (rapid reaction) and CF_3CHN_2 (slow reaction)[49] as follows:

$$\underset{\text{cis,trans}}{MeO_2C\text{-}\overset{H}{C}=\overset{H}{C}\text{-}CO_2Me} > \underset{\text{cis,trans}}{CF_3\text{-}\overset{H}{C}=\overset{H}{C}\text{-}CF_3} > CF_3CH=CH_2 > CH_2=CHBr >$$

$$CH_2=CH_2 > CH_2=CH=CH_3 > \underset{\text{cis,trans}}{CH_3\text{-}\overset{H}{C}=\overset{H}{C}\text{-}CH_3} >> CH_2=CHF,$$

$$CF_2=CH_2 > CF_3\text{-}\overset{F}{C}=CF_2$$

As can be seen, fluoroalkyl substituents lead to higher reactivity. A prime example is the addition of diazomethane to olefin[51] 99 (equation (1-30)).



(1-30)

99 100 101

a, Y=H,X=CO_2Me	> 99%	-
b, Y=H,X=COPh	100%	-
c, Y=H,X=CN	70%	30%
d, Y=CF_3,X=CF_3	100%	-

These are precisely the results to be expected for the more usual cycloaddition process[52] in which the dipolarophile LUMO, 1,3-dipole HOMO interaction is the dominant effect. These results are explained by Huisgen[48] that conjugation is important in dispersing the charge which result from formation of one bond slightly ahead of the other. For trifluoromethyl group, however, the dispersal can only be due to an inductive electron withdrawal which could equally explain the reactivity of the carbonyl substituents. The

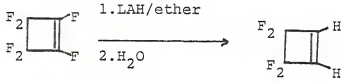
high electronegativity of fluorine which would, on this basis, be expected to lead to a high reactivity of vinyl fluoride is countered by the strong π-donating effect of the fluorine, which prevents electron transfer to the double bond by the 1,3-dipole.

Recently, Bryce et al.[53] came out with similar conclusions about the effect of a fluorine and a trifluoroalkyl group on a double bond in its reaction with diazomethane and he elegantly rationalized it, on the basis of the Frontier Molecular Orbital approach, as due to polarization of the double bond as a result of different orbital coefficient and the carbon atom which is attached to fluorine becomes the preferred site for reaction as in 102.

102

It is reasonable to consider that in the reaction of 1,3-dipole with fluorinated olefins, the 1,3-dipole can be thought of as being a nucleophilic agent ($\bar{C}H_2\overset{+}{N}_2$) while the fluorinated olefin can be thought of as being electrophilic. Thus, a CF_3 group would stabilize a carbanion

intermediate, inductively, while a directly bonded fluorine would destabilize it, mesomerically. There are some examples[54] in the literature to substantiate this argument (equation (1-31)).



(1-31)

43 45

Here the CF_2-groups inductively stabilize the carbanion intermediates generated by the hydride attack on each carbon of the double bond of 43.

CHAPTER 2
THERMOLYSIS OF 6,6,7,7-TETRAFLUORO-2,3-DIAZABICYCLO[3.2.0]HEX-2-ENE (106)

Introduction

In 1972 Bergman[55] reported that bicyclopyrazoline (51) underwent thermal deazetation via two competing mechanistic pathways (figure 2-1). Among the products is

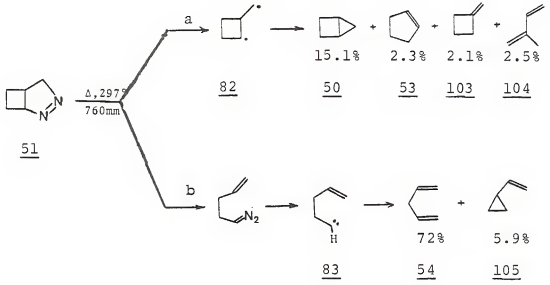


Figure 2-1. Thermolysis Products of Pyrazoline 51.

bicyclo[2.1.0]pentane (50), which was assumed to be formed only from the 1,3-diradical (82),[55] is a unique molecule which can be thought as being formed from cyclobutane and cyclopropane rings fused together at C_1-C_4 bond. Most of the strain in this molecule is accommodating this bond,

and such strain can be released by the rearrangement process to give a stable cyclopentene (53). This process has an Ea of 46.6 kcal/mol[26] as compared to 65.4 kcal/mol for cyclopropane[28,56] itself.

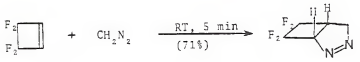
According to figure 2-1, Bergman showed that compounds 54 (1,4-pentadiene) and 105 (vinylcyclopropane) are the only products derived from the carbene intermediate (83).

In view of the fact that the strength of the C-C bond in cyclopropane can be drastically affected by geminal difluorosubstitution it was considered of significance to determine if similar effects might be present in a cyclobutane system in this case specifically fused to a cyclopropane ring. It could be remembered that in general, fluorination kinetically stabilizes a cyclobutane ring toward thermal fragmentations.[14,15]

The system utilized to test this effect was 2,2,3,3-tetrafluorobicyclo[2.1.0]pentane (107) (equation (2-2)). According to figure 2-1, the major product 54 (1,4-pentadiene) likely formed from the carbene intermediate (83).[55] If the same mechanism is followed to make 107 (equation (2-2)), the tetrafluoro analog of 83 would not be able to give the analogous diene due to the location of fluorine substituent. Consequently the yield of the desired compound (107) should be increased.

Results and Discussion

Synthesis of 2,2,3,3-tetrafluorobicyclo[2.1.0]pentane (107) was achieved through the thermal (equation (2-2)) or photochemical (equation (2-6)) deazetation of pyrazoline 106 which was prepared via the facile addition of diazomethane to 3,3,4,4-tetrafluorocyclobutene[54] (45) (equation (2-1)).



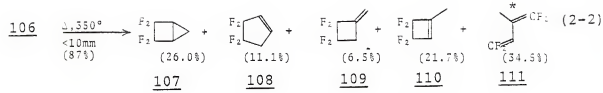
(2-1)

45 106

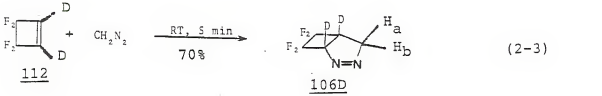
The bicyclic pyrazoline (106) is a white solid melting at 52°C. At temperatures close to 0°C it remained stable as the Δ^1-pyrazoline even when left for one hour at room temperature. In comparison to other fluorinated pyrazolines[53] this one is considerably more stable with respect to its isomerization to Δ^2- or Δ^3-pyrazolines.[57]

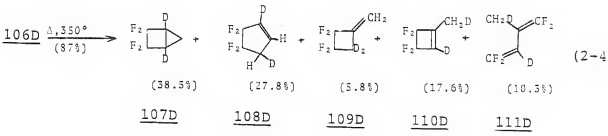
The bicyclic pyrazoline (106) was pyrolyzed at 350°C in a flow system wherein 106 was allowed to evaporate, in vacuo, and pass into a heated zone where partial deazetation occured (~75% conversion). A mixture* of five isomeric products was produced in yield of 68% (equation (2-2)).

* Preparative Gas Chromatography was used to separate the components of most isomeric mixtures throughout this text.



The structures of 106-111 were unambiguously characterized through spectral data (^{1}H, ^{19}F, ^{13}C) and further by syntheses of their deuterated analogs 106D-111D in analogous manner to the undeuterated compounds (equation (2-3) and (2-4)).





* λmax = 254 nm

The complex AB system of H_aH_b in the ^{1}H-NMR of 106 was resolved into a simple AB pattern in its deuterated analog. A similar simplification of the ^{1}H-NMR spectra of compounds 107D-111D was also observed and resulted in structure verification for all isomers. The results of thermal deazetation of 106 and 106D are perhaps best rationalized in terms of competitive formation of diradical and carbene intermediates 113 and 115, figure 2-2, the latter via retro-1,3-dipolar cycloaddition. While all observed products may be construed as having been formed from the single 1,3-diradical intermediate (113), involvement of the carbene 115 cannot be ruled

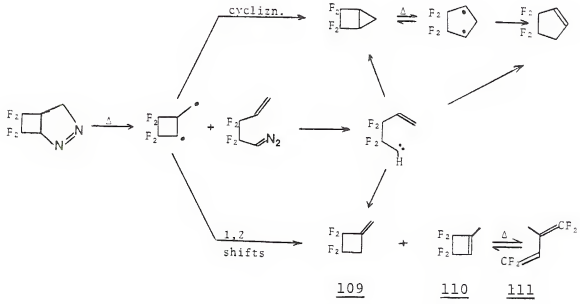


Figure 2-2. Mechanism of Products Formation from Thermolysis of Pyrazoline 106.

out as at least a partial source of 107, 108 and 109. As expected, products analogous to 1,4-pentadiene (54) and vinylcyclopropane (105) observed by Bergman[55] in the hydrocarbon system (derived from the carbene) are not possible in this case because of the location of fluorine substituents, but such a carbene as 115 could well cycloadd intramolecularly to form 107 or insert into vinylic C-H bonds to form 108 and 109. While the deuterium-labelling experiment does not allow distinction of these two mechanistic pathways, it does exclude the possibility of direct formation of the tetrafluorocyclopentene (108) from diradical 113 by a ring expansion as illustrated in equation (2-5). Cyclopentene (108) therefore is most likely formed from the tetrafluorobicyclopentane (107) via diradical 116 with

(2-5)

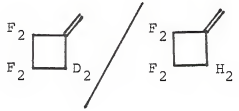
113D

117

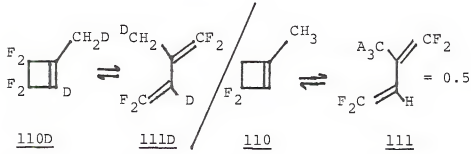
(not observed)

perhaps some contribution from the carbene process. A control pyrolysis demonstrated that 107 will convert thermally to 108 at temperature >350°C (see text below).

The lack of observation of an inhibitory isotope effect in formation of 108D [the yield of (108D) is in fact more than double that of (108)] rules out carbene insertion as the major pathway for formation of 108. As expected one does observe isotope effects in the formation of methylcyclobutene 110D and methylenecyclobutane 109D.



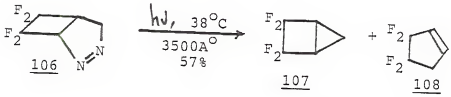
109D 109



110D 111D 110 111

Photolytic Synthesis of 2,2,3,3-Tetrafluorobicyclo[2.1.0]pentane (107)

Photochemical deazetation of the tetrafluoropyrazoline (106), as a neat liquid in vacuo, using 2500 Å radiation for 15-20 hours, led to the formation (57% yield) of only 107 and 108 in the relative yields of 56 and 44% respectively (equation (2-6)).



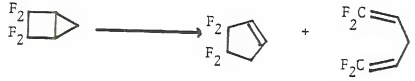
(2-6)

It was not certain whether (108) formed from (107) (which itself likely formed from the 1,3-diradical 113), or from a carbene intermediate 115 via insertion into vinylic C-H bond. In a control photolysis it was found that 107 did not convert significantly to 108 under the photolysis conditions. This implies that an intermediate other than 1,3-diradical is operative as well. A 1,3-diradical was expected and often is assumed to be formed in photolyses of pyrazolines with two and three fused-rings.[41,42] Species like 109 and 110 would have been observed if the 1,3-diradical was the sole intermediate. In addition comparison of the yield ratio of the olefinic product with the cyclopropane

product with others in the literature[55] indicates that the retro 1,3-dioplar cycloaddition is likely another main course in the photolysis of 106 producing carbene 115 besides 1,3-diradical (113) which according to figure (2-2) can form the observed products. A carbene intermediate has been proposed as being the main intermediate in photolysis of smaller ring-fused pyrazolines.[39b]

Thermal Rearrangement of 2,2,3,3-Tetrafluorobicyclo[2.1.0]pentane (107)

Thermal rearrangement of 107 to 3,3,4,4-tetrafluorocyclopentene (108) in the gas phase (10-30 mm pressure) was carried out in a well-conditioned pyrex vessel, and proceeded smoothly, following excellent first-order kinetics with only a small amount of competitive fragmentation of 118 being observed, as shown in equation (2-7).



108 (93.5%) + 118 (6.5%) (2-7)

The yield was determined by direct GC analysis of the gaseous product mixture. Products were identified by comparison of their GC retention time with those of authentic samples. Rates of thermal rearrangement were measured at six temperatures. Data obtained are given in table 2-1.

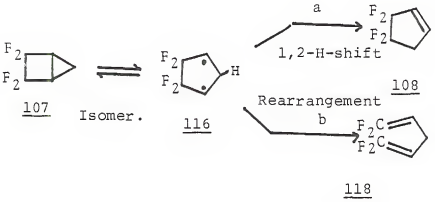
Table 2-1. Rate Constants for Thermal Rearrangement of 107 to 108.

$T(\pm 0.1)^{\circ}C$	$kx10^{5}\ s^{-1}$
334.5	2.46 ± 0.01
340.0	3.95 ± 0.02
346.0	6.01 ± 0.04
352.0	8.50 ± 0.05
358.0	16.60 ± 0.20
364.5	20.90 ± 0.10

An Arrhenius plot of the rate data gave a good straight line and the frequency factor and energy of activation were calculated by the method of linear least squares. This gave the following Arrhenius equation for the rearrangement of tetrafluorobicyclopentane (107) to tetrafluorocyclopentene (108) (equation (2-8)).

$$\log k/s = 14.9 \pm 0.4 - (54.2 \pm 1.1 \text{ kcal/mol})/RT \ln 10. \quad (2\text{-}8)$$

The relative rate of formation of 1,4-diene product (118) from 107 at 346°C was 0.069, which corresponds to a $\Delta\Delta G^{\neq}$ of 3.1 kcal/mol. If one assumes that log A for 107→118 is 15.3 then one obtains an activation energy of 58.6 kcal/mol for thermal rearrangement of tetrafluorobicyclopentane (107) to 1,4-pentadiene (118). These results can be summarized by equation (2-9).

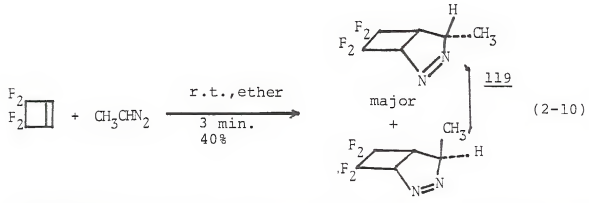


107 116 108 118 (2-9)

	E_a kcal/mol	Relative k	log A
107-108	54.2(46.6)*	14.4	14.9(14.6)*
107-118	58.6(52.5)*	1	15.3(14.4)*

* Numbers in parantheses correspond to the hydrocarbon for the analogous rearrangement.

If one compares the activation energy for conversion of 107 to 108 with the activation energy for the analogous rearrangement of the hydrocarbon system (Ea=46.6 kcal/mol, log A=14.6), one can see that the rearrangement of 107 is significantly inhibited (ΔEa=7.6 kcal/mol) relative to the hydrocarbon rearrangement. As indicated before, 116 is the presumed intermediate in this rearrangement (see 52 equation (1-17)). A significant remaining question then is whether the observed increase in activation energy is due to an increase in the C_1-C_4 bond dissociation energy D(C-C) of the tetrafluorobicyclopentane (107) or whether it is due to a decrease in the rate of the subsequent 1,2-hydrogen shift process of the 4,4,5,5-tetrafluorocyclopentane-1,3-diyl intermediate (116). In order to answer this question, the exo- and endo- 5-methyl-2,2,3,3-tetrafluorobicyclo[2.1.0]-pentanes (120) and (121) were synthesized in a manner analogous to 107. Addition of an ethereal solution of diazoethane to 3,3,4,4-tetrafluorocyclobutene resulted in a 40% yield of 4-methylpyrazoline (119) (equation (2-10)). The structure of 119 was tentatively assigned as the trans isomer

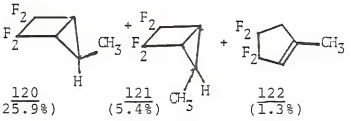


(2-10)

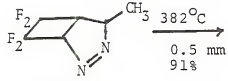
* Numbers in parantheses correspond to the hydrocarbon for the analogous rearrangement.

by homonuclear decoupling experiments (60 MHz) and from the sharp doublet of the CH_3 group in ^{1}H-NMR of 119. However the regiochemical assignment was not that critical since deazetation of either of the two isomers should give the 5-methyl derivative of 107 required for our desired purpose.

The bicyclic methylpyrazoline (119) which was pyrolyzed at 382°C and 0.5 mm pressure produced a mixture of six isomers (120)-(125) (equation (2-11)) in 91% yield. Spectral

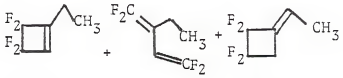


120 (25.9%) 121 (5.4%) 122 (1.3%)



119

382°C, 0.5 mm, 91% (2-11)



123 (40.3%) 124 (25.2%) 125 (1.9%)

data (^{1}H, ^{19}F, ^{13}C) were used to unambiguously identify compounds 120-123. The structure for each of 124 and 125 was presumed based on the thermolysis of the tetrafluoropyrazoline (106). No effort was made to isolate compounds 124 and 125 from each other.

A certain distinction between the structure of (120) and (121) was achieved by homonuclear decoupling experiments of the ^{1}H-NMR (300 MHz) spectra, figures (2-1, 2-2). Irradiation of the methyl group of the exo-isomer (120) changed the quartet of H_b into a broad singlet (figure 2-1), while irradiation of the methyl group of the endo-isomer (121) changed the quartet of triplet of H_b into a simple triplet (figure 2-2), resulting from the coupling of H_b facing both Ha's protons. This indicates that the cis coupling constant in the endo-isomer (J=6.9 Hz H_b by both Ha's) is larger than their trans coupling in the exo-isomer, a situation which was documented in the case of the parent hydrocarbon[58] (50).

Table 2-2. Rate Constants for Isomerization of 121 to 120.

$T(\pm 0.1)^{o}C$	$k_1 \times 10^5$	$k_{-1} \times 10^5$
209.0	3.33	0.171
217.0	6.65	0.368
223.5	10.40	0.575
230.5	20.07	1.140
236.5	30.55	1.790
243.0	49.56	3.004

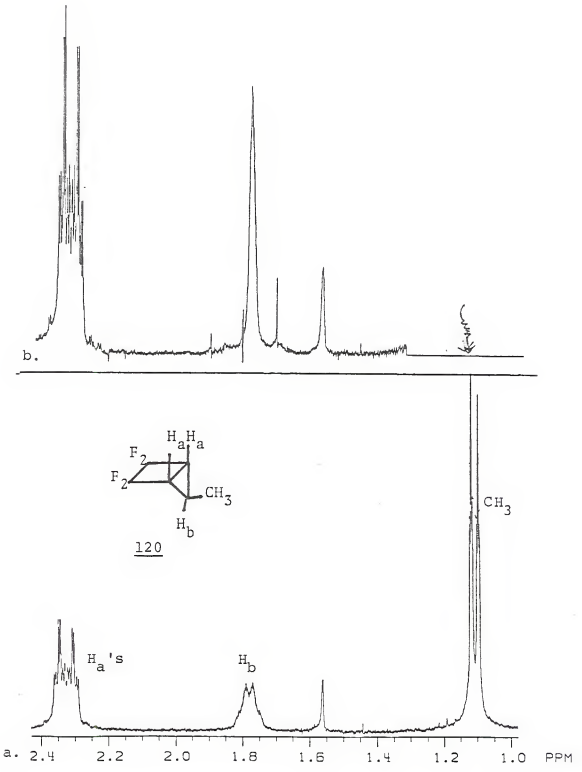


Figure 2-3. ^1H NNR Spectrum of 120.a.normal. b.CH_3 decoupled.

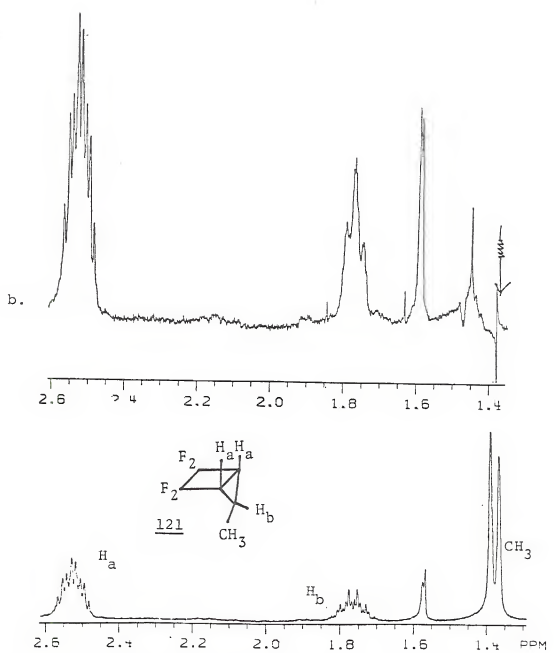
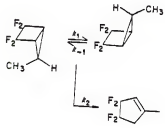


Figure 2-4. ^{1}H NMR Spectrum of 121. a. normal b. CH_3 decoupled.

Ther thermal isomerization of 121 to 120 was examined kinetically in the gas phase in a well-conditioned pyrex vessel. The kinetic results are illustrated in Figure 2-5. Rates of thermal isomerization were measured at six temperatures. Data obtained are given in table (2-2).



122

log A = 13.4
E_a + 39.4 kcal/mol
H = - 2.38 kcal/mol
S = 0.95 e.u.

$k_2(358.0^{\circ}C) = 2.68 \times 10^{-4} s^{-1}$
k_2(relative to 107)=1.97

Figure 2-5. Isomerization of 121 to 120 and the Corresponding Activation Parameters.

The Arrhenius plots of rates gave the least-squares analysis:

$$\log k_1 s^{-1} = 13.4 \pm 0.3 - (39.4 \pm 0.8 \text{ kcal/mol})/RT \ln 10$$

$$\log k_{-1} s^{-1} = 13.2 \pm 0.3 - (41.8 \pm 0.8 \text{ kcal/mol})/RT \ln 10$$

Equilibrium constants of the thermal isomerization were measured at eight temperatures starting from the exo-isomer (120). Data obtained are given in table (2-3).

Table 2-3. Equilibrium Constants for the Isomerization of 120 to 121.

T °C	K = 121/120
217.0	18.83
223.5	17.99
230.0	17.30
236.25	17.06
243.0	16.47
250.0	16.08
257.0	15.60
262.5	15.11

A van't Hoff plot of the equilibrium data gave a good straight line and a reaction enthalpy and reaction entropy as indicated below

$$\Delta H = -2.38 \text{ kcal/mol}$$

$$\Delta S = 0.95 \text{ e.u.}$$

All activation and equilibrium parameters are tabulated in Figure 2-5.

A comparison of these data with the other examples of methyl substituted analogs of unfluorinated bicyclo[2.1.0]-pentanes (table 1-3)[27a] would appear to indicate that the presence of four fluorine substituents in 2,2,3,3-tetra-fluorobicyclo[2.1.0]pentane (107) has little effect upon the C_1-C_4 bond dissociation energy. A necessary corollary of such a conclusion is that the observed inhibition of the tetrafluorocyclopentene formation observed in the rearrange-ment of 107 must derive from an inhibition of the 1,2-hydrogen shift process of the intermediate 4,4,5,5-tetra-fluorocyclopentane-1,3-diyl species (116).

To further document the data obtained for the thermal rearrangement of 107 to 108, a single rate constant was measured for the thermal rearrangement of the exo methyl isomer 120 to 122 (1-methyl 3,3,4,4-tetrafluorocyclopentene) in the gas phase in a well-conditioned pyrex vessel at temperatures 358°C. Rate constant obtained is given below

$$k_{(120 \rightarrow 122)} = 2.68 \times 10^{-4}\ s^{-1} \text{ at } 358^{\circ}C$$

if one assumes a log A value, for conversion of exo-methyl-bicyclopentane-F4 (120) to methylcyclopentene-F4 (122), to be equal to the value of log A (14.9) found in the rearrange-ment of bicyclopentane-F4 (107) to cyclopentene-F4 (108) then the Ea for 120 to 122 rearrangement is 53.24 kcal/mol. A result that is consistent with the expected methyl effect on bicyclopentane rearrangements (table 1-3).

A potential energy diagram (figure 2-6) can represent our data as compared with the hydrocarbon analog.

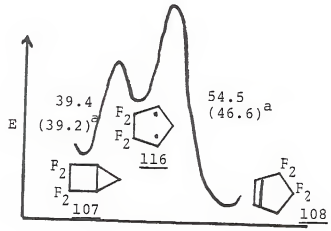


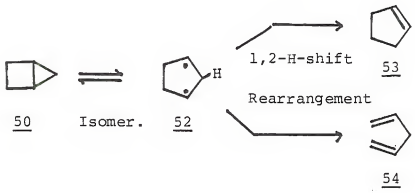
Figure 2-6. Potential Energy Diagram for the Thermal Rearrangement of 107 to 108 in Comparison with the Hydrocarbon.

a. numbers in parantheses are the corresponding energies for the hydrocarbon analog in kcal/mol.

The source of this unexpected inhibition can be rationalized in two ways.

Firstly, there is more retardation in transition state required for the overlapping of the migrating H-orbital to the free electron (orbital allignment). Secondly, the

fluorine substituents are decreasing the strain in the cyclobutane ring of 107. Concerning the first rationale let us consider the hydrocarbon system itself (50), and equation 1-17 as rewritten below



(1-17)

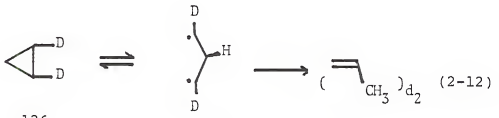
$$E_{a,\ 50\ -\ 53} = 46.6 \text{ kcal/mol}$$

$$E_{a',\ 50\ -\ 54} = 52.5 \text{ kcal/mol}$$

Halberstadt et al.[26b] estimated the total energy required for the rearrangement of 50 to 53 as represented by the above equation to be equal to 34 kcal/mol as derived

from the sum of their wrong appraisal of 19±4 kcal/mol for reaction (1) (C_1-C_4 bond energy) and the palusible 15 kcal/mol for reaction (2) (1,2-hydrogen shift). Since this value for Ea did not agree with their experimental Ea (46.6 kcal/mol) therefore they suggested a mechanism in which the transition state does not go through an intermediate such as diradical 52 in which the C_1-C_4 bond is completely broken and that the rearrangement is a concerted process. However their conclusion contradicts their experimental results which suggest a radical mechanism is more possible.

In 1964 Steel et al.[26a] compared their results for the above reaction with cyclopropane[28,56] rearrangement, equation (2-12),

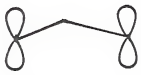


126 127 128 (2-12)

E_a (126-127) = 65.1 kcal/mol

E_a (126-128) = 65.4 kcal/mol

and estimated a higher Ea for reaction (2) in equation (1-17) (14.9 kcal/mol) as compared to reaction (2a) in equation (2-12) ($\leq$9.5 kcal/mol). The authors concluded that the orbital of the migrating hydrogen does not overlap as effectively with that of the free electron on the adjacent carbon in the case of the cyclic biradical (52) as it does in the case of the acyclic biradical (127) (equation (2-12). In addition based on his calculation Benson[59] seems to agree with Steel's rationale about the inhibition of the 1,2-hydrogen migration in 52 relative to 127. Moreover this also agrees with the theoretical calculation of Doubleday[25] who indicated that depending on what kind of geometry the diradical may assume, i.e. (0,0), (0,90) or (90,90) as depicted by 129 a, b and c and also whether a singlet (S) or a triplet (T) diradicals are involved, the barrier to H-transfer on the singlet surface



a. (0,0)

129

b. (0,90)

c. (90,90)

lies about 5.2-5.7 kcal/mol above the surface of the favorable barrier for cyclization, which occurs at the intersection of (S), (T) species (E_{ST}=0) where the T to S crossing at (90,90) geometry can lead to cyclopropane product without activation at that intersection. Although Doubleday was studying the effect of why photolytically generated triplet species diradical leads predominantly to cyclopropane product while singlet diradical (direct photolysis) leads to olefin product (1,2-H-shift), he also considered the thermal reaction on the singlet surface correlating it with the Arrhenius factor and entropy of activation as follows. The barrier for cyclopropane formation can almost be thought of as having the E_{ST}=0 line as a free internal rotation, yielding a favorable entropy of activation. On the other hand, the H-transfer to form olefin is expected to have much tighter geometrical requirements, i.e. entropically unfavorable process.

The above mentioned reasoning concerning the effect of the intermediate's rigidity on the inhibition of the 1,2-H-shift may also be operative here and applied on the case of the tetrafluoro system as follows. The four fluorine atoms (figure 2-7) may interact with the radical orbitals in different ways. Firstly is the inductive withdrawing effect of the two CF_2 moieties. This will induce a polarization of the radicals towards the fluorines. Such effect diminishes the tendency of the radical to undergo reactions by decreasing the spin density at the radical centers.[60a]

Polar effect of some halogens other than fluorine may be little in special cases,[60b] the high electronegative nature of four fluorine atoms could be more significant.[61,62]

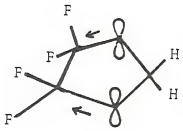


Figure 2-7. Fluorine Inductive Effect in 1,3-Diradical 116.

A second and more important kind of interaction is the overlap between the half-filled carbon 2p-orbital and the filled non-bonding p-orbital on the fluorine (Anchimeric Interaction), figure 2-8.

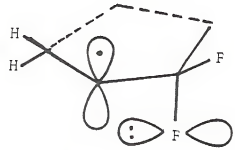


Figure 2-8. Anchimeric Interaction of Fluorine non-bonding Orbital with the Radical Half Filled Orbital in 1,3-Diradical 116.

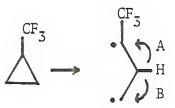
This overlap fixes the ring conformation (anchimeric fixation) inhibiting the radical from attending the required geometry for overlapping and hence increases the rigidity of the transition state for proper allignment of the migrating hydrogen radical orbital. In other words this interaction actually increases the 1,3-diradical stability. As a consequence of this interaction a higher energy was needed to overcome this kind of overlap in comparison to the hydrocarbon which definitely lacks such unique type of interaction. This kind of overlapping is very well studied and documented in other systems,[62] especially in comparing fluorine with other halogens (e.g. chlorine with larger 3P orbital). It has been found that, due to the fluorine appropriate orbital size as being a second period element, fluorine is the most effective halogen in this kind of interaction.[62a,b] Some related data in literature are given in table 2-4.

Table 2-4. Chlorination of Mono-substituted Cycloalkanes at 100°C in the Gas Phase: Trans/cis Ratios.[a]

compound	trans-1,2 / cis-1,2	trans-1,3 / cis-1,3	trans-1,4 / cis-1,4
Fluorocyclohexane	40.5	1.04	1.79
Chlorocyclopentane	16.1	1.76	(b)
Chlorocyclohexane	10.5	2.01	0.77
Chlorocycloheptane	4.1	1.10	1.09
Methylcyclopentane	1.3	-	(b)

[a] ref. 62a,b. [b] Not applicable.

A prime example of this effect is the rearrangement[62c] of trifluoromethylcyclopropane to 1-butene and 2-butenes as illustrated in figure 2-9.

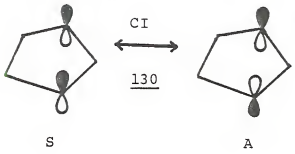


	E_a kcal/mol
A ⟶ CF_3-CH_2-CH=CH_2	67.3(62.0)[a]
B ⟶ CF_3-CH=CH-CH_3 cis and trans	65.0,trans(61.9)[a] 65.2,cis (64.4)[a]

Figure 2-9[a] Thermal Rearrangement of Trifluoromethylcyclopropane. [a] corresponding activation energies for the methylcyclopropane, ref. 62c.

The important thing to note is the relative rates ratios of k_A/k_B=0.24 compared to a ratio of 1.1 for methylcyclopropane which indicate preferentail transfer of an H atom toward (k_A) or away from (k_B) the trifluoromethyl group. However, these results were only rationalized as originating from the inductive effect due to fluorine substitution.[62b]

This effect in general can be understood more if one consider the two types of molecular orbital of bicyclopentane depicted in 130 below.[63]



The (S) MO is the ground state and symmetric would be doubly occupied (HOMO) and the corresponding Antibonding and anti-symmetric (A) orbital would be unoccupied (LUMO). Through configuration interaction (CI) upon ring opening of bicyclopentane (50) the above ordering would be reversed as indicated in figure 2-6. One might expect the fluorines as substituents would render the partially flattened bicyclopentane to react

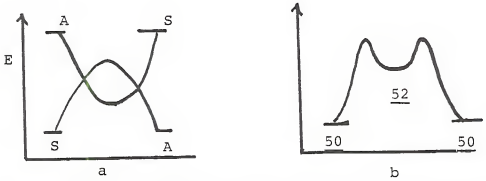


Figure 2-10. [a] Orbital Energies of 52. [b] State Correlation Diagram. [c] from ref. 63.

in a manner appropriate to either type of C(1)-C(4) molecular orbital symmetry, for instance with the hydrogen orbital as a two center two electron as an A component, or intramolecularly as an S orbital through collapse to bicyclopentane. The latter case could explain the normal activation barrier found for the isomerization of the fluorinated bicyclopentane.

Now a totally different approach will be considered to explain the increment in Ea of the fluorinated bicyclopentane. This concerns the steric effect of fluorines on bicyclopentane rearrangement. As we will see below, it is interesting to find that looking at the fluorine effect from different perspective (steric) and using different model system to compare with, one can come up with a conclusion exactly opposite to the one just made before, ie. the 1,2-hydrogen shift is normal but the flip-flop process is unusually fast.

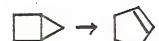
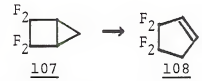
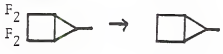
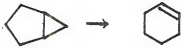
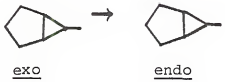
In general, fluorination kinetically stabilizes a cyclobutane ring toward thermal fragmentation. An unusual fluorine effect on cyclobutane could be seen when one compares bond strength and bond lengths. In spite of the total bond strengthening of cyclobutane ring by fluorine substitution, it is curious to note that c-C_4F_8 has longer, 1.566 Å vs 1.548 Å, yet stronger C-C bonds than C-C_4H_8.[12a] This bond lengthening effect can result in diminishing the strain energy (E_S) in the ring relative to c-C_4H_8. From ΔH_f^o of c-C_4F_8

(-368.7 kcal/mol) and sum of four perfluoro $C(F)_2(CF_2)_2$ group values[8,12a] (-377.6 kcal/mol) the E_S of $c\text{-}C_4F_8$ was calculated to be only 8.9 kcal/mol i.e. $c\text{-}C_4F_8$ is about 17.6 kcal/mol less strained than cyclobutane. It is not unusual to predict that the relief of strain in tetrafluorocyclobutane would fall in the same line as the case for the perfluoro, especially if one compares their Ea's of fragmentation. They are in the order of 69.7 kcal/mol for $c\text{-}C_5F_4H_4$ and 74.2 kcal/mol for $c\text{-}C_4F_8$ as compared to the $c\text{-}C_4H_8$ which is 62.5 kcal/mol. These numbers indicate that Ea's are higher for cyclobutane with more fluorine substitution, i.e. less strained ring fragment less easily and vis versa.

Applying the above argument on the tetrafluorobicyclopentane, that fluorines do relieve the strain of cyclobutane ring to a degree in between the hydrocarbon, bicyclo[2.1.0]pentane, and the bicyclo[3.1.0]hexane as a reference model here, one can see that the observed Ea for the tetrafluorobicyclopentane falls in the right order as it would be expected (table 2-5)). The strain energy of tetrafluorocyclobutane can be calculated* similarly to $c\text{-}C_4F_8$ since its experimental ΔH_f^o is known[64] (-202 kcal/mol) as compared to ΔH_f^o of $c\text{-}C_4F_8$ (-368 kcal/mol) and $c\text{-}C_4H_8$ (+36 kcal/mol). The calculation** showed that there is 17.7 kcal/mol strain energy in tetrafluorocyclobutane, still less strained than cyclobutane itself by about 8 kcal/mol. Thus as in

*See Appendix A
**Although is dubious

Table 2-5. Comparison of Activation and Strain Energies in Thermal Rearrangement of Bicyclic Compounds.

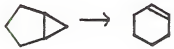
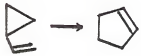
	E_a kcal/mol	E_s kcal/mol	Ref.
1.  50 → 53	45.6	55.3[a]	26
61 exo → 62 endo	38.9		27a
2.  107 → 108	54.2	27.5+17.7[b]	
 120 exo → 121 endo	39.4		
3.  3.1.0	57.4	33.9[a]	65
 exo → endo	not known		

[a] ref. 59. [b] Calculation based on ref. 96 and Appendix A.

table 2-5, the Ea for bicyclo[3.1.0]hexane (3.1.0) entry 3, is larger than Ea for 107 and even much more compared with (50), is consistent with the smaller strain associated with the bridge bond α in (3.1.0) compared to the strain in bond α of the other two bicyclic compounds (107) and (50). Accordingly since bond α in 107 is less strained than bond α in 50 then one would expect a higher Ea for the isomerization process, entry 2, table 2-5, as compared with the more strained system (50). The experimental value for this process, 39.4 kcal/mol, implies a rather unusual fast rate operative in the isomerization process.

This rate enhancement can easily be understood by studying the systems in table 2-6. Comparing the Ea's of reactions in table 2-6, indicates that there is an interesting combination of two reaction - facilitating effects that can be found in which "ring strain" and "electron delocalization" act together. Therefore the diradical intermediate is more stabilized with the presence of fluorine atoms which results in rate enhancement for the isomerization process. In conclusion fluorine atoms in thetrafluorbicyclopentane reduced the rate of 1,2-hydrogen migration by Anchimeric interaction with the 1,3-diradical in comparison to the hydrocarbon and conversely they have an enhancing effect on its epimeric isomerization in comparison with the less strained next homolog, bicyclo[3.1.0]hexane. An accurate measure of the strain energy in tetrafluorocyclobutane ring

Table 2-6. Electron Delocalization Effect on Activation Energies of Thermal Rearrangement of Bicyclic Compounds.

		E_a kcal/mol	E_a(a-b) kcal/mol	Ref.
1.		57.4		
a.			7.2	65
b.		50.2		
2.		65.4		28
a.			11.8	
b.		49.6		66
3.		32.7		
a.			5.82	18c
b.		26.88		

and the Ea for the isomerization of bicyclo[3.1.0]hexane may lead to a clear distinction between the two possible effects suggested.

CHAPTER 3
SYNTHESIS AND THERMAL REARRANGEMENT OF 6,6- AND 7,7-DIFLUORO-2,3-DIAZABICYCLO-[3.2.0]HEPT-2-ENES. ATTEMPTED SYNTHESIS OF 2,2-DIFLUORO-BICYCLO[2.1.0]PENTANE

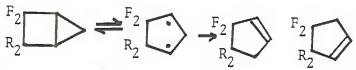
Syntheses of 3,3-Difluorocyclobutene

The first classical way for constructing a four membered ring was Perkin's malonic ester syntheses and their modification.[67] Ideal syntheses of cyclobutane and cyclobutene would be afforded by addition of ehtylene to ethylene or acetylene, respectively, but these reactions do not appear to have so far been achieved in good yields. Substituted ethylenes and ketenes have been converted to cyclobutane derivatives in thermal, or photochemical reactions.[68] However, with few exceptions the yields are low or the products are not well-suited for further transformations. The discovery that fluorinated ethylenes will often thermally dimerize[69a] or add to other unsaturated compounds[69b] to give high yields of cyclobutane derivatives provides an excellent synthetic route to a wide variety of fluorinated cyclobutanes.[70]

Results and Discussion

The results obtained from the thermolysis of 2,2,3,3-tetrafluorobicyclo[2.1.0]pentane (107) encouraged the extension

of the study to the fluorinated homolog, 2,2-difluorobicyclo[2.1.0]pentane (131) so as to gain insight into fluorine effects on the mechanistic aspects of this reaction (equation (3-1)). By removing the symmetry imposed in tetrafluorocyclopentane-1,3-diradical (116) an intermediate like difluorocyclopentane-1,3-diradical (132) would create a favoritism for the 1,2-hydrogen shift process. This intermediate would yield 133 and/or 134 in a ratio which would be



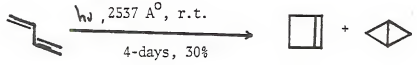
(3-1)

107, R=F 116 108 108

131, R=H 132 133 134

in accord with the prediction made earlier as a result of fluorine interaction with the free radicals. To this purpose it was attempted to synthesis 2,2-difluorobicyclo-[2.1.0]pentane (131) by an analogous procedure for the tetrafluoro analog (107). Consequently the synthesis of 3,3-difluorocyclobutene (139) was sought first, then upon reaction with diazomethane it would give the corresponding pyrazoline and ultimately 131 via deazetation. Due to the

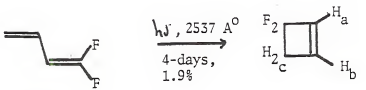
lack of any synthetic approach to 3,3-difluorocyclobutene in the literature, the first attempt was based on the work of Srinivasan[71] that photolysis of 5% solution of butadiene in cyclohexane yielded cyclobutene and bicyclobutane in 10:1 ratio, respectively (equation (3-2)).



(3-2)

135 136 137

Following the same photolytic conditions above, 1,1-difluoro-1,3-butadien[72] gave 1.9% of the 3,3-difluorocyclobutene (139) but no 2,2-difluorobicyclo[1.1.0]butane (137) was detected (equation (3-3)).



(3-3)

138 139

Compound 139 was characterized by ^{1}H, ^{19}F and ^{13}C NMR. A characteristic feature of its ^{1}H- and ^{19}F-NMR is the large coupling between the two fluorines and proton-H_b shown as

a doublet (14 Hz with H_b) of triplet (3 Hz with Hc) of doublet (1.5 Hz with Ha) (figure (3-2)).

Because of the poor yield of the photolytic method and the difficulty involved in isolation of very dilute samples the following approach was designed and successfully employed to give an overall yield of 47% of 3,3-difluorocyclobutanecarboxylic acid (144), figure 3-1, which was characterized through ^1H, ^{19}F and ^{13}C NMR. Compound 143

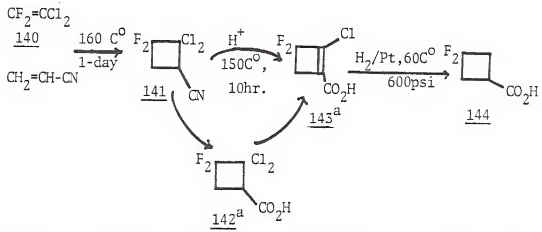
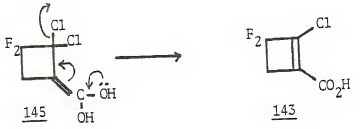


Figure 3-1. Synthesis of 3,3-Difluorocyclobutanecarboxylic Acid (144). [a] Ref. 69b.

(monochlorodifulorocyclobutene acid)[69b] was observed as the major product upon hydrolysis[73] of dichlorodifluorocarbonitrile 141[70c] beside a trace amount of dichlorodifluoro acid 142[69b] in the reaction mixture. This result can easily be explained based on the acid catalyzed enolization of 142 to give enol 145 (equation (3-4)) which then can eliminate a chloride ion as shown below. Other possibility is the

direct elimination of HCl by chloride ion[74] as indicated in equation 3-5.

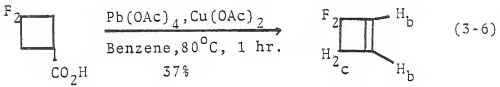


(3-4)

(3-5)

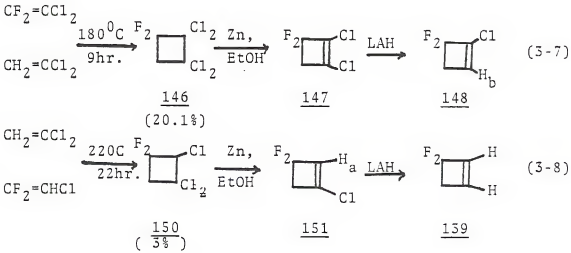
Compound 143 so as compound 147 (1,2-dichloro-3,3-difluorocyclobutene) below resisted hydrogenation using Rhodium (Rh) as a catalyst (even under vigorous conditions of 1800 psi of H_2) inspite of the effectiveness of Rh catalytic hydrogenation on other noncyclic and strain free olefins.[75] Compound 142 resisted hydrogenalysis totally even when platinum was used and high hydrogen pressure.

Synthesis of 3,3-difluorocyclobutene (139) was again achieved in 37% yield by oxidative decarboxylation[76] of the acid 144 (equation (3-6)) using lead tetraacetate and a catalytic amount of cupric diacetate.[76]



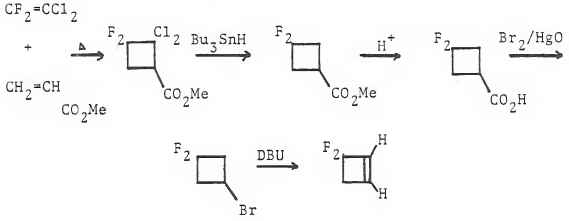
144 139 (3-6)

Compound 139 obtained by the decarboxylative method gave exactly identical spectroscopic features exhibited by the same product obtained via photolysis of 1,1-difluoro-1,3-butadiene (138). The spectroscopic characterization of 139 was further implemented with no doubt upon the syntheses of compounds 148 and 151 as shown in equations (3-7) and (3-8).



Using ^{19}F-NMR as a probe compound 148 showed a signal which consist of doublet of triplet (J_d=14Hz, J_t≅3 Hz, 60 MHz) while 151 showed a triplet of doublet (J_t=2.83 Hz, J =1.45 Hz, 300 MHz)(figure 3-1). The unexpected large coupling between fluorines and the diagonally cross proton (H_b) in 139 can derive from the W-form situtation of both interacting atoms. Some models in literature agree with the assignment made here [77] (figure 3-2).

During the course of this work, concomitantly, the synthesis of 3,3-difluorocyclobutene (139) was also achieved by other group[7,8] following similar route as shown below.



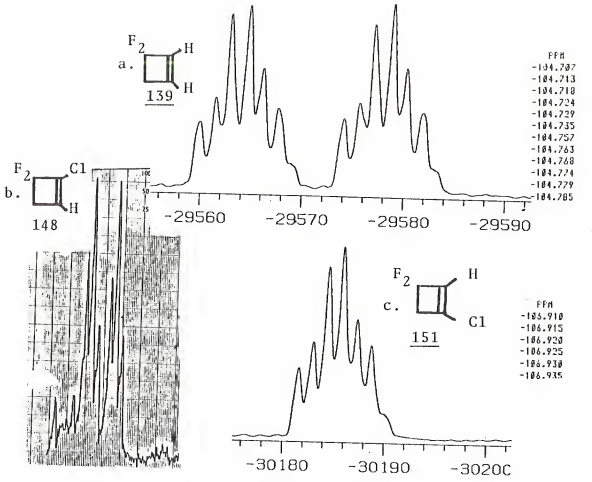


Figure 3-2. ^{19}F NMR Spectra(expanded) of [a] 139(300 MHz). [b] 148(60 MHz). [c] 151(300 MHz).

Synthesis of 6,6-and 7,7-difluoro-diazabicyclo[3.2.0]hept-2-enes

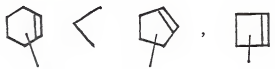
Recently Bryce et al.[53] investigated a systematic study directed at establishing the effects of fluorine and perfluoroalkyl as substituent on the reactivity and regiospecificity of alkenes toward diazomethane. According to their results they concluded that reactivity increases with the number of perfluoroalkyl groups on olefins in the following order

$$(R_f)_2C{=}C(R_f)_2 \gg (R_f)_2C{=}CF(R_f) \gg (R_f)_2C{=}CF_2, R_fCF{=}CFR_f$$

and

$$(R_f)_2C{=}C(R_f)_2 > CF_3C{=}CCF_3 > CF_3CH{=}CHCF_3 > CF_3CF{=}CHCF_3 > CF_3CF{=}CFCF_3.$$

While perfluorocyclohexene did not react with diazomethane, both of perfluoro-cyclopentene and -cyclo-butene gave the corresponding Δ^2-dihydropyrazole, albeit very slowly indeed. The perfluorocycloalkenes are all, obviously, electronically equivalent to systems such as RFCF=CFRF, but there is a clear variation in reactivity in the order shown below

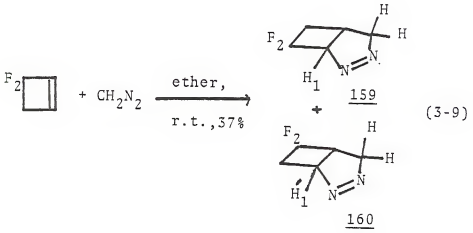


152 153 43

Although experimental yields are not a quantitative measure for obsolute olefin reactivity perhaps it would give an idea about the relative ease of olefin reaction with diazomethane when the identical experimental conditions are applied (table 3-1).

Results and Discussion

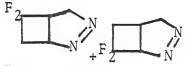
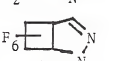
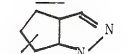
Addition of diazomethane solution in ether to 3,3-difluorocyclobutene at room temperature for one day led to the formation (23% yield) of only pyrazolines 159 and 160 in relative ratio of 2.4:1 (equation (3-9)).



(3-9)

The structural assignment of each of pyrazoline 159 (the major isomer) and 160 was based on spectral analyses of IR, ^{1}H- and ^{19}F-NMR and also by comparison with tetrafluoropyrazoline (106). Proton H_1 in the major isomer 159 is

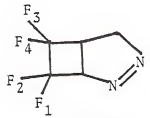
Table 3-1. Yields Comparison in Reaction of Diazomethane with Fluorinated Olefins at Room Temperature.

Olefin	Product	Time(yield)	Ref.
		4-days (72%)	24,40
		1-day (37%)	
		5-min. (70%)	
	 154	14-days (55%)	53
153	 155	14-days (25%)	=
152	N.R.	14-days	=
156	N.R.	14-days	=
$CF_3CF=CF_2$ 157	N.R.	14-days	=
CF_3-CF=CF-CF_3 158	N.R	15-days	=

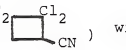
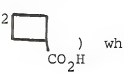
further downfield than H_1' in the minor isomer 160 and its chemical shift almost identical with the similar proton in the tetrafluoropyrazoline 106.

The identity of each isomer as far as the position of the difluoro group is concerned was based on fluorine NMR spectrum which also by its integration was able to determine the ratio established for both isomers.

In studying model compounds in the literature[70a,79] it can be observed that the difference in chemical shifts of geminal non-equivalent fluorines in cyclobutane rings is dependent on the type of substituent on both α-carbons. Sigma or pi electron withdrawals tend to decrease the chemical shift difference e.g. halogens, C=N,N, and O. Let us first refer to the tetrafluoropyrazoline (106).



106

The difference in chemical shifts between F_1 and F_2 equal $\Delta\nu$=834 Hz (100 MHz) while $\Delta\nu$=564.8 Hz for F_3 and F_4 That is because F_1,F_2 are α to the carbon which is substituted by N atom and F_3,F_4 are α to the carbon with CH_2 group as a substituent. Applying the above argument to the difluoro-pyrazolines (159), 160) resulted in the conclusion that the pyrazoline with the CF_2 group situated α to the carbon with N atom substituent (159) is the major isomer (by integration) since the fluorines with $\Delta\nu$=1055.48 Hz (300 MHz) or 351.8 Hz (100 MHz) integrated 2.4 times than that of the other two AB fluorines (160) with $\Delta\nu$=2486.46 Hz (300 MHz) or 828.82 Hz (100 MHz) present in the same spectrum of the mixture (figure 3-3). Also compound 141  with a C Cl_2 group α to CF_2 exhibits $\Delta\nu$=480 Hz (60 MHz) as compared to compound 144  which exhibits $\Delta\nu$=800 Hz (60 MHz) in its fluorine NMR spectra.

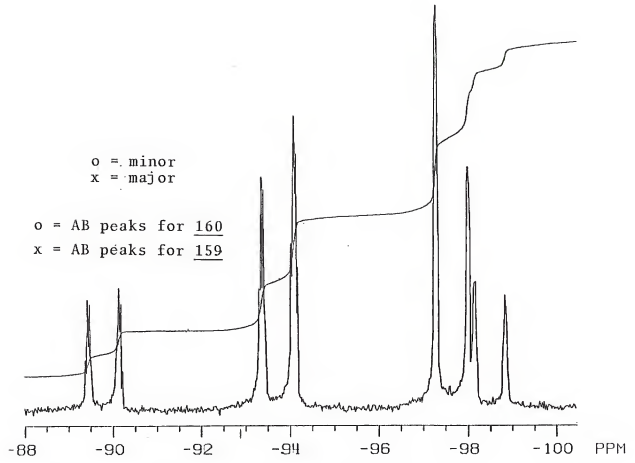
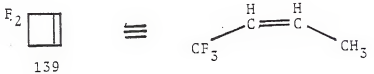


Figure 3-3. ^{19}F NMR Spectrum of Mixture of Pyrazoline 159 and 160.

It would be reasonable to rationalize the regioselectivity observed in equation (3-9) on the basis of two mechanistic pathways, self consistent with each other as a concerted 1,3-dipolar cycloaddition, HOMO-LUMO interaction, or as a nucleophilic addition controlled by the relative stabilities of intermediate carbanion. Let us consider the 1,3-dipole path first. If frontier molecular orbitals govern the reactivity of fluorinated alkenes with diazomethane, then interaction of the LUMO of the fluorinated alkene with the HOMO of diazomethane would be the controlling process. The effect of fluorine atoms and perfluoroalkyl groups on olefinic carbon coefficients has been discussed by Bryce et al.[53] who concluded that the number and position of perfluoroalkyl groups will be very important and generally decrease the orbital coefficient of the LUMO of sp^2-carbon directly attached to it.

As was mentioned earlier the purfluorocycloalkenes are all electronically equivalent to systems such as $R_FCF=CFR_F$. Applying the same analogy to 3,3-difluorocyclobutene (139) would indicate its equivalency to $R_FCH=CHR$ i.e. the CF_2 group can act as a perfluoroalkyl group on a noncyclic alkene[53,54] as shown below. Based on Bryce's perfluoroalkyl



139

effect on alkene's double bond coefficient it can be said that the coefficient of the LUMO orbital on C(2) (figure 3-4) is smaller than the one on C(1) which results in a clear

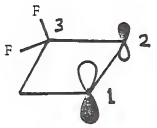


Figure 3-4. LUMO of 139 .

polarization of the system with the carbon (1) of the double bond becoming the preferred site for attachment of the 1,3-dipole and hence the major isomer 7,7-difluoro-pyrazoline (159) was preferred. This reasoning is related to the rationale made earlier concerning the fluorine effect on 1,2-hydrogen shift in tetrafluorocyclopentane-1,3-diyl radical (116).

Concerning the polar or partially polar character of the intermediates or transition state leading to difluoro-pyrazoline 159 and 160, one would obviously expect that the carbanion A in figure 3-5 is more stable than B.

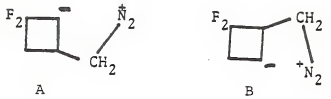


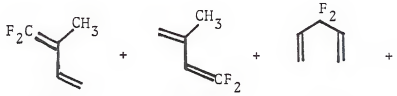
Figure 3-5. Polar Transition State for Diazomethane Reaction with 3,3-Difluorocyclobutene (139).

This arises from the fact that fluorine attached on α-position from a carbanion is strongly stabilizing.[19]

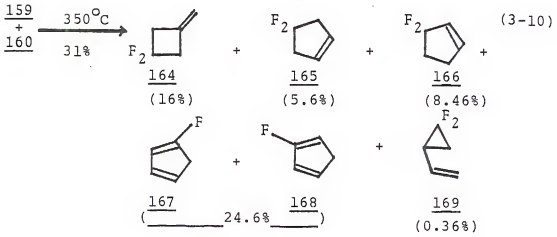
Thermolysis of 6,6- and 7,7-difluorobicyclo-[3.2.0]hept-2-enes. Attempted synthesis of 2,2-difluorobicyclo[2.1.0]pentane: Results and Discussion

No attempt was made to isolate the two isomeric pyrazolines 159 and 160 from each other since both would produce the desired 2,2-difluorobicyclo[2.1.0]pentane (131) resulting from nitrogen loss. In addition most of the fluorinated unsymmetrical pyrazolines are prone to isomerization to Δ^2-pyrazoline.[53]

The mixture of bicyclic pyrazolines (159, 160) was pyrolized at 350°C in the same manner as tetrafluoropyrazoline 106. A mixture of nine isomeric products was produced in yield of 31% (equation (3-10)).



161 (6.52%) + 162 (10.56%) + 163 (27.77%) +



159 + 160 —350°C, 31%→ 164 (16%) + 165 (5.6%) + 166 (8.46%) + 167 + 168 (24.6%) + 169 (0.36%) (3-10)

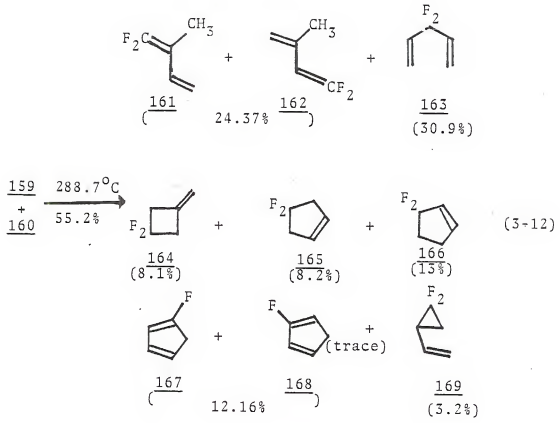
The structures of 161-169 were unambiguously characterized through spectral data. Surprisingly the desired compound, 2,2-difluorobicyclo[2.1.0]pentane (131), was not observed. Before reaching undue conclusions it was thought that compound 131 might not be able to survive the thermolysis temperature and perhaps went on and thermolyzed further to 165 and 166[80] each of which then could give 167 and 168 respectively via HF loss.

Pyrolyzing pyrazolines 159 and 160 at lower temperature, 205°C, resulted in quantitative recovery of both pyrazolines (equation (3-11)). To this point the

$$159,160 \xrightarrow{205\ ^{\circ}C} \text{No thermolysis occured} \qquad (3\text{-}11)$$

recovery of starting materials was fortunate in the sense of limiting our temperature range. Logically next temperature was chosen as an average of the above two.

Thermolysis of pyrazolines 159 and 160 at 288.75°C gave a mixture of nine isomeric products, which was similar to that formed at 350°C, differing only in yield (55%) and product rations (equation (3-12)).



As in the earlier described deazetation, two kinds of intermediates are likely involved in leading to the products observed on thermolysis of 159 and 160 (figure 3-6). The first thing worth noting in comparison to the tetrafluoropyrazoline (106) results is the observation of 3,3-difluor-1,4-pentadiene(163), and 2,2-difluorovinylcyclopropane (169) as products. Such compounds were not possible in the thermolysis of 106 because of the location of the fluorine

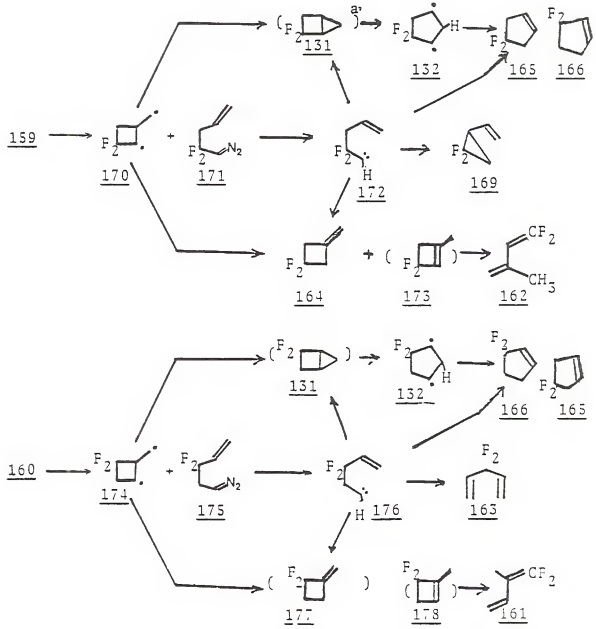


Figure 3-5. Mechanism of Products Formation from the Thermolysis of Pyrazolines 159 and 160.
[a] Compounds in parantheses were not observed.

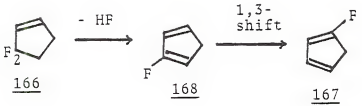
substituents. Indeed replacing two fluorine atoms by hydrogens as in carbene 172 resulted in formation of vinyldifluorocyclopropane (169). Carbene 172 is the only intermediate that could lead to 169, since the other carbene (176), which is possible only from the minor pyrazoline isomer (160), could lead only to 1,4-pentadiene (163). Virtually all minor pyrazoline 160 went to 163.

Comparison of the yield of vinylcyclopropane (169) at low temperature (288.7°) with that at higher temperature (350°C) shows that its yield decreased by about ca. 10 times at the higher temperature. This is in agreement with Bergman's observation[40] that as the temperature raised carbene type products, like diene 163 and vinyl cyclopropane 169, decreased. Similar effect can be seen in case of 1,4-diene 163 but to a lesser extent. This yield variation could also be due to the possible fact that the difluorovinylcyclopropane (169) rearranged[80] to 3,3-difluorocyclopentene (166). This implies that the decrement in carbene type products at higher temperatures does not necessarily mean that the formation of carbene intermediate would be less likely.[40]

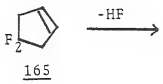
Formation of 1,3-dienes 161 and 162 (161/162=0.61) is conclusive that generation of the 1,3-diradical intermediates 174 and 170 did occur indeed. These dienes can only be formed from their corresponding cyclic structures,[66] cyclobutenes 178 and 173, respectively, both of these were not observed in the pyrolysis mixture. That implies the fast ring opening

of both cyclobutenes 173 and 178 under thermolysis conditions. A question could be asked here, whether the 1,3-diradical (170, 174) closes up to the desired compound 131(difluorobicyclopentane) or not. To answer this question let us recall the deuterium experiment done with the tetrafluoropyrazoline 106, and which concluded that cyclopentene product mainly formed from tetrafluorobicyclopentane (107), via 1,3-diradical closure which is also in agreement with Bergman's conclusion.[40] Hence the 1,3-diradical did close to give compound 131 which under the experimental conditions thermolyzed totally to both difluorocyclopentenes 165 and 166. However if the 1,3-diradical (170,174) did not close to give 131 then its only remaining paths are the 1,2-hydrogen shifts to yield methylenecyclobutane (164) and cyclobutene products (173, 178) and ultimately the butadienes 161 and 162.

Compound 167 (1-monofluorocyclopentadiene) is virtually the exclusive product observed, resulting from HF loss, with the other trace amount of unidentified product tentatively assigned as being 168 (2-fluorocyclopentadiene). Compound 167 was unambiguously characterized through ^{1}H, ^{19}F and ^{13}C NMR spectrosocpy. It can be formed by HF loss from compound 166 to give 168 which then isomerizes to 167 (equation (3-13)). A precedent for this type of process is presented in literature[81] with the mentioning that compound 165 did not show such HF loss. However if 165 lost HF molecule it would directly give 167 (equation (3-14)). In addition no spectral data

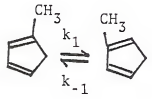


(3-13)



(3-14)

were reported concerning either of 167 or 168. A similar equilibration has been observed when the fluorine atom in 167 and 168 is replaced by a methyl group[82] (equation (3-15)).



$k_1 = 8.2 \times 10^{-6}$, $k_{-1} = 5.8 \times 10^{-6}$ at 50°C (3-15)

Another possibility for not observing compound 131 might also be considered as to be due to unsymmetrical nature of this molecule causing some polarization in cyclopropane ring which inducing a new mode of rearrangement process, i.e. fission of the periferal cyclopropane bonds as in

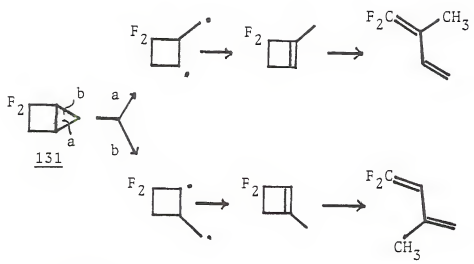
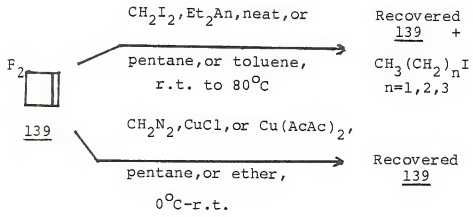


Figure 3-7. Possible Products from the Periferal Bonds Cleavage of the Cyclopropane Ring in 131.

scheme 3-4. Although the difference in Ea between breaking any of the periferal bonds and the bridgebond is at least 14 kcal/mol in the case of the hydrocarbon,[26a] the two fluorine atoms in this case might contribute to make such energy differences comparable. The parent bicyclopentane (50) did undergo such type of fission to about 0.05% to give isoprene.[26a] Moreover this type of fission also has been suggested in the pyrolyses of other substituted (not fluorinated) bicyclopentanes.[30c]

In any case, it was necessary to seek some other mild route to the desired compound 131. Indeed a different route was tried (equation (3-16)) but unfortunately addition of methylene carbene-carbenoid[83] species to 3,3-difluoro-cyclobutene (139) at room temperature or even up to 80°C did not produce any appreciable amount of 2,2-difluoro-



bicyclo[2.1.0]pentane (131). Instead the starting material was recovered along with some iodoalkane homologs.

CHAPTER 4
THERMODYNAMIC EFFECT OF FLUORINE ON
CYCLOBUTENE-BUTADIENE EQUILIBRIUM

Introduction

The thermal isomerization of cyclobutene to butadiene has been thoroughly investigated.[18c] The reaction is unimolecular and irreversible and rate data yielded the Arrhenius equation (equation (4-1)). The energy of

$$\log k\ s^{-1} = 13.26 - 32700/2.303\ RT \qquad (4\text{-}1)$$

Activation for the isomerization of cyclobutene compared with that for the decomposition of cyclobutane (Ea=62 kcal/mol)[15] has been discussed by Walter.[84] Unlike cyclobutane, the isomerization of cyclobutene requires the rupture of only one bond (C_3-C_4) and this bond is already weakened relative to cyclobutane by the increased strain (30.6 kcal/mol compared to cyclobutane (26.9 kcal/mol))[85] in the ring due to the presence of a double bond. Also the resonance energy of the diene formed could be considered to help the lowering of the Ea.

The effect of substituents, mono-alkyls and halogens other than fluorine on the electrocyclic interconversion of cyclobutene and 1,3-butadiene pair have been the subject of

many theoretical and experimental[18c,86a-g,87] investigations. By the use of a theoretical model proposed by Carpenter[86a] it can be qualitatively predicted that any substituent at the double bond of cyclobutene should decrease the rate of conrotatory ring opening due to the inductive effect of the substituent resulting in a lengthening of the C=C bond and hence decreasing the strain in the C_3-C_4 bond.[18c,86b] On the other hand substitution at the 3 and 4 positions should increase the rate of the reaction due to repulsive steric type and/or electronic stabilization of the "transient" diradical by substituent.[86b] Moreover, Di-substitution in the 3-position is accompanied by a large increase in the Ea which was attributed to be largely a steric effect.[86c] However, recently Kirmse et al.[88a] explained the effect of substituent in positions 3 and 4 on the energetics of conrotatory electrocyclic ring opening of cyclobutene ring as totally due to an electronic* factor but not steric. This was based on the frontier MO interactions of the substituent HOMO with the cyclobutene C_3-C_4 σ-bond LUMO which can result in greater stabilization when the substituent is a better electron-donor and moving outwardly in the conrotatory ring opening. These predictions have received considerable experimental support[18c,86c,87,88] (table 4-1).

*This is also in agreement with a similar hypothesis originally made by Dolbier[88b] about the preference (9.2 kcal/mol) of the inward conrotatory ring opening of perfluoro-trans-3,4-dimethyl-cyclobutene relative to the outward mode.

Table 4-1. Activation Parameters for the Isomerization of Cyclobutenes.

compound[a]	E_a kcal/mol	log A	relative $k.10^4$ at 175c[b]
	32.7	13.26	17
	35.1	13.79	4.6
	31.55	13.53	160
	36.04	13.84	1.8
	33.00	13.65	33
	33.39	13.52	16
	36.09	13.93	-
	37.03	13.90	-
(trans)	33.59	13.85	56
(cis)	37.36	14.10	0.9
	40	-	0.45

compound[c]	E_a kcal/mol	log A
	33.64	
	29.4	13.07
(cis)	35.6	13.87
(trans)	25.7	12.96
(cis)	34.0	13.68
(trans)	30.6	14.01
	23.5	12.68
(cis)	27.8	12.89
(cis)	31.6	12.66
(cis)	29.1	12.85
(cis)	25.5	11.71

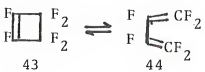
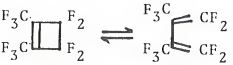
[a] ref. 86c,87. [b] ref. 87b. [c] ref. 87b,88a.

The effect of halogen[87] (chlorine) as a substituent on the isomerization is similar, but a little bigger, to the alkyl effect with regard to the position of substitution and the energetic and rate influences on the isomerization (table 4-1).

Frey examined the example of 3,3,4,4-tetrafluorocyclobutene[19] conversion to the corresponding butadiene, showing that fluorine effect on C_3-C_4 follows the same prediction made earlier i.e. rate retardation due to halogen substitutions. This also can be explained based on Kirmse's[88a] prediction. Since the ring opening of 3,3,4,4-tetra substituted cyclobutene necessitates that two of the substituents on C_3 and C_4 to move outward while the other two inward, it may seem that the destabilization by the inwardly rotating fluorines affecting the rate in this molecule. This rate is comparable with other fluorinated cyclobutenes (e.g. 43 and 47, table 4-2) since C_3-C_4 are commonly substituted with four fluorine atoms, but the equilibrium lies well on side of the diene. These results along with the others in literature are given in table 4-2.

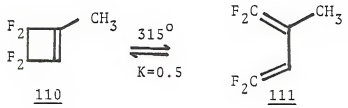
Results and Discussion

Under the conditions fo deazetation of tetrafluoropyrazoline (106), 1-methyl-3,3,4,4-tetrafluorocyclobutene (110) was found to have partially equilibrated with its butadiene isomer 111. When allowed to fully equilibrate at 315°C under static gas phase conditions, an equilibrium value of

	System	K(315°)	Δ H[a]	ΔS	E_a[a]	Ref.
1.	136 ⇌ 135	9×10^{3}	-8	4.5	32.5	86d
2.	 43 ⇌ 44	5.6×10^{-3}	11.7	9.6	47.1	2
3.		3.3	2.5	6.65	-	86e
4.	45 ⇌ 46	77.5	-	-	47.9	
5.		16.0	1.1	7.4	-	86e
6.	 47 ⇌ 48	8.4	0.4	4.9	46.0	20

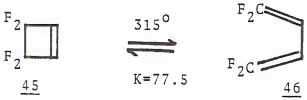
[a] In kcal/mol.

0.5 (K=111/110) was obtained. The interconversion was also tested starting from 2-methyl-1,1,4,4-tetrafluoro-1,3-butadiene (111) and an equilibrium value of 2.01 ($K=\frac{110}{111}$) was obtained (equation (4-2)).



110 111 (4-2)

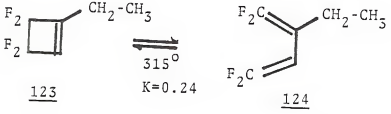
The presence of so much cyclobutene isomer 110 at equilibrium was unexpected in view of the fact that Frey[19] has observed a much greater thermodynamic preference for the butadiene isomer 46 in the system without methyl group



45 46 (4-3)

(table 1-2). Indeed we observed only 1.3% of 45 in equilibrium at 315°C (equation (4-3), table 4-3). A comparison of the 110 ⇄ 111 and 45 ⇄ 46 equilibria indicates a rather dramatic thermodynamic effect ($\Delta\Delta G^{o}$=5.9 kcal/mol) due to the presence (or absence) of the methyl substituent.

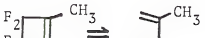
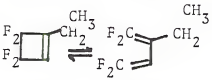
Similarly substitution of an ethyl for the methyl substituent leads to an even greater shift in equilibrium (i.e K=0.24 at 315°C)(equation (4-4)). However, when



123 124 (4-4)

the equilibrium of the 3,3-difluorocyclobutene system (139) was tested at 315°C in the gas phase under static conditions, the rate of its conversion to the butadiene was too fast to be measured. Lowering the temperature to 237°C allowed the rate measurement and again the 1,1-difluoro-1,3-butadiene (138) was thermodynamically preferred to an equilibrium value ≯945. These data are given in table 4-3.

Table 4-3. Equilibrium Constants and Relative Rates for Cyclobutenes-Butadienes Interconversion.

	System	K($T^{o}C$)	E_a kcal/mol	Relative k, (at 600°K)
1.	139 ⇌ 138	945(237)	40.32[a]	86.33
2.	45 ⇌ 46	77.5(315)	47.9	1.0
3.	 110 ⇌ 111	0.5(315)	49.77[b]	0.2
4.	 123 ⇌ 124	0.24	50.21[b]	0.14

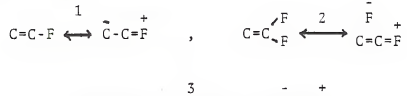
[a] Calculated based on the parent hydrocarbon, assumed both have same log A.
[b] Calculated based on the reaction 2 in table, assumed both have same log A.

To understand the driving force for this dramatic alkyl effect requires an understanding of the various thermodynamic stabilities of butadienes relative to cyclobutenes. We can limit ourself between the two extreme reactions depicted in table 4-2, entries 1 (represents the hydrocarbon) and 2 (represents the perfluorocyclobutene). In reaction 1 the butadiene is the more stable species in the equilibrium, while in reaction 2 the perfluorocyclobutene is more stable. Virtually all other fluorinated cyclobutene-butadiene systems fall between these two extremes. Let us consider the butadiene stability first from which the corresponding and dependent relative cyclobutene stability can then be deduced. Any destabilization in a particular butadiene would be counterbalanced by an increase in the amount of the respective cyclobutene which would be in equilibrium.

The first thing to consider is the electronic effect of fluorines on double bond. The electronic effect on stabilization of double bonds by α and π electron donors and acceptors substituents has been studied.[89a] These studies indicated that the mono-methoxy and mono-fluoro substituents in spite of being highly electronegative are among the best double bond stabilizers. This stabilization presumed to be derived as a result of the electron delocalization arising from the overlap of the filled 2p orbitals of the substituent with the 2pπ systems of the carbon-carbon double bond.[89b]

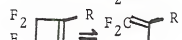
Other substituents that have less stabilizing ability on a double bond relative to methoxy and fluorine were considered to have less delocalization effect.

While the alkyl group stabilization on a double bond is additive in going from 1-alkyl to 1,2-dialkyl,[89] the addition of a second methoxy[89a] or fluorine[12b,53] substituent is destabilizing. This effect can be rationalized by comparison of the possible resonance forms resulting from the electron delocalization in double bonds as was discussed in chapter 1.



Resonance interaction 1 is stabilizing because of charge delocalization while resonance interaction 3 is destabilizing because of the opposing effect of each fluorine on termini of carbon-carbon double bond as a result of electron repulsion.

Referring back to cyclobutene-butadiene equilibria under the present study and comparing entries 1 and 2 with 3 and 4 as rewritten below one can draw similar resonance forms for the 1,1-difluoro- and 1,1,4,4-tetrafluorobutadienes which has destabilizing component similar to resonance 2. However, the more important interaction in the 2-alkyl substituted tetrafluorobutadienes is similar to the one in resonance 3 showing the opposing effect of

	T°C	K	
	315	945	(4-5)
	315	77.5	(4-6)
	315	0.5,R=CH_3 0.24,R=Et	(4-7)

substituents which perhaps is the major effect in destabilizing these dienes. So the vicinal electronic interaction is a major factor in determining butadiene stability relative to cyclobutene. This vicinal fluorine-methyl effect in such kinds of butadienes has a resemblance to the fluorine-fluorine vicinal effect as reflected from the heats of hydrogenation of the olefins[12b] outlined below

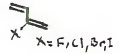
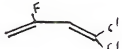
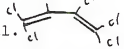
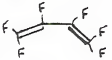
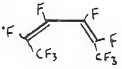
olefin	ΔH_H^o kcal/mol
$CH_2=CH_2$	-32.6±0.3
$CH_2=CHF$	-29.7±0.8
$CH_2=CF_2$	-38.8±2.8
$CHF=CF_2$	-45.7±5.5

The second thing to consider which could affect the stability of butadienes in the equilibria under the present study is the steric interactions of the 1,1,3-type[90a,b,91a,b,92] which induces some destabilization in butadiene and force it to attain a cis (skew) conformation rather than the commonly more stable S-trans (table 4-4).

Comparison of reaction (4-7) with (4-5) and (4-6) indicates that introducing an alkyl group in position 2 of butadiene or position 1 of cyclobutene favors the cyclobutene thermodynamically more than the butadiene. We can see that the alkyl group creates the 1,1,3-type of interaction in the butadiene which would likely force the diene to twist into the cis (skew) form and therefore destabilized it. In fact the 1,1,3-type interaction is doubled in the perhalogenated butadienes, entries 11 (perchlorobutadiene), 12 (perfluorobutadiene) and 13 (perfluoro-2,4-hexadiene) (table 4-4). In these cases both steric and electronic factors are operative to certain extents. The steric repulsion can be minimized if the perchlorobutadiene twists around the single bond and attains the cis (skew) conformation. However, the perfluorobutadiene the fluorine-fluorine overlap can be maximized in the cis (skew) form.[91b,c] In fact perfluorobutadiene exists totally in the skew form.[90g] In the perfluorohexadiene perhaps both effects could be important. This twisting can also bring some destabilization in the butadiene by decreasing its conjugation energy as was evident from the observed carbon-carbon bond distances.[90g]

In addition to the destabilizing alkyl interaction in the butadiene, alkyl substitution on the cyclobutene double bond, as was discussed earlier, stabilizes the cyclobutene ring in the sense of decreasing the strain by electron donation inductively which results in lengthening of the double bond and therefore strengthening C_3-C_4 bond.

Table 4-4. Effect of Substituent on Conformation of 1,3-Butadienes.

		trans	cis	ϕ[a]	Ref.
1.		✓		180	90c
2.		✓		180	90c
3.		✓		180	90d
4.		mainly	b		90a
5.		✓			90e
6.			✓	50	90b
7.			✓	50	90b
8.		✓			90a
9.		✓		180	90f
10.		✓		180	90f
11.			✓	0 90	90b
12.			✓	47	90g
13.					88

[a] Dihedral angle. [b] Did not exclude the cis isomer.

CHAPTER 5
EXPERIMENTAL

Introduction

Infrared spectra were determined on Perkin-Elmer 283B spectrophotometer and absorption bands are reported in cm^{-1}. The spectra of neat liquids were determined as films between KBr plates. Gas phase spectra were determined using a gas IR cell with KBr windows and a 5-cm path length using 10 to 30 mm pressure of sample.

NMR spectra were recorded on a Nicolet NT-300, a Jeol FX-100, a Varian XL-100 or a Varian EM 360L spectrometer. ^{1}H and ^{13}C chemical shifts (δ) are reported as ppm downfield of internal TMS. ^{19}F chemical shifts (ϕ) are reported in ppm upfield of internal $CFCl_3$. All NMR spectra were obtained at ambient temperature in $CDCl_3$ or CCl_4 except for pyrazoline mixture 159, 160 which was ran at $-10^{\circ}C$.

Mass spectra and exact masses were determined on an AEI-MS 30 spectrometer at 70 ev.

The preparative GC separations were performed on a Varian Aerography 90-P gas chromatograph with thermal conductivity detector. The gas phase samples were analyzed using a Hewlett-Packard 5710A or 5790A gas chromatograph with a flame-ionization detector in conjunction with a Hewlett-Packard 3380S or 3390A recording integrator, respectively.

Melting points were determined with a Thomas-Hoover capillary melting point apparatus and are uncorrected.

Procedures

1,2,3,3,4,4-Hexafluorocyclobutene, 101

Based on a published procedure,[54] 27.6g (0.169 mole) 81% of 101 was obtained: IR, gas phase 1790, 1400, 1150, 960 cm^{-1}. ^{19}F NMR ($CDCl_3$, 60 MHz) ϕ 120.5 (d of d J=20 Hz, 10.6 Hz), 129.89 ppm (d of t, virtual pentate, J=21 Hz, 10.5 Hz).

3,3,4,4-Tetrafluorocyclobutene 45

Identical procedure to the published[54] one was followed to obtain 4g (0.031 mole) 23% of a colorless liquid b.p= 54-55°C of 45: ^1H NMR ($CDCl_3$, 60 MHz) δ 6.74 ppm (m); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 111.10 ppm (S); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 123.45 (t, J_{CF}=287 Hz), 143.27 ppm (p).

6,6,7,7-Tetrafluoro-2,3-diazabicyclo[3.2.0]hept-2-ene, 106

An ether solution of diazomethane (35 ml) was prepared from 3.5g (17.5 mmoles) N-methyl-N-nitroso-P-toluenesulfonamide.[93a] The solution was vacuum transferred to a 160 mL glass tube with a rotoflow teflon stopcock and 2.2g (17.5 mmoles) tetrafluorocyclobutene were condensed into the tube, which was sealed under vacuum. After five minutes at room temperature, the clear, colorless solution was concentrated by rotary evaporation at 200 mm pressure and the ether was removed completely under 3 mm pressure. The residue was a white solid 2.06g (0.0122 moles) 71% was stored on dry ice

under nitrogen: m.p. 25.5°C; IR (neat film) 1545, 1425, 990, 910, 800, 730, 680 cm^{-1}; ^{1}H NMR (CCl_4, 100 MHz) δ 3.07 (br.m 1H), 4.83 (d of d, J_{AB}=19 Hz, J=8 Hz 1H), 5.08 (d of t, J_{AB}= 18 Hz, J=3 Hz, (H), 5.73 ppm (br. m, 1H); ^{19}F NMR (CCl_4, 100 MHz) ϕ 113 (J_{FF}=223 Hz), 115 (J_{FF}=218 Hz), 121 (J_{FF}=223 Hz), 124 ppm (J_{FF}=218 Hz); mass spectrum gave M^+ 168.0317±0.0021 (13 ppm), calcualted for $C_5H_4F_4N_2$ 168.0310 dev.=0.0006 (4.1 ppm).

Thermolysis of Pyrazoline 106

2,2,3,3-Tetrafluorobicyclo[2.1.0]pentane 107, 3,3,4,4-tetrafluorocyclopentene 108, 1-(methylene)-2,2,3,3-tetrafluorocyclobutane 109, 1-methyl-3,3,4,4-tetrafluorocyclobutene 110, and 2-methyl-1,1,4,4-tetrafluoro-1,3-butadiene 111.

Through a 22 cm by 2.5 cm Vigreux column heated at 350°C was vacuum transferred 0.87g (5.2 mmoles) pyrazoline 106 over a period of 4 hours at a pressure of 0.25-0.4mm. A total of 500 mg (69%) crude liquid pyrolysate was collected in a vacuum trap at liquid-nitrogen temperature. The products were isolated by prep GC (20 ft by 1/4 in. in 10% DNP at 55°C, 33 mL/min. to give:

a. 39 mg (5.34%) of 107: IR (gas phase), 3100, 3015, 1370, 1330, 1150, 1065, 970, 875, 780, 580, 465 cm^{-1}; ^{1}H NMR (CCl_4, 60 MHz) δ 1.43 (m, 2H), 2.55 ppm (m, 2H); ^{19}F NMR (CCl_4, 100 MHz), ϕ 116.6 (mid point) AB, J_{AB}=209.5 Hz, Δν=1447.1 Hz); ^{13}C NMR (CCl_4, 300 MHz) δ 7.39 (C_5), 21.8 (C_1),

115.7 ppm (CF_2, complex t, J_{CF}=285.8 Hz); mass spectrum gave M^+ 140.0239±0.0016 (11.8 ppm), Cacd. for $C_5H_4F_4$ 140.0249 dev.=0.0013, (9.8 ppm).

b. 31 mg (4.25%) of 108: IR (gas phase), 3095, 1610, 1500, 1440, 1370, 1345, 1015, 915, 770, 730, 585, 470 cm^{-1}; ^1H NMR (CCl_4, 60 MHz) δ 2.92 (t of t, J=12 Hz, J=3 Hz, 2H), 6.03 (d of t, J=4 Hz, J=2 Hz, 1H), 6.42 ppm (m, 1H); ^{19}F NMR (CCl_4, 100 MHz) ϕ 113 (br. s, 2F), 118 (5, J=11.2 Hz, 2F); ^{13}C NMR (CCl_4, 300 MHz) δ 39.2 (t, J_{CF}=26.5 Hz), 120 (m), 126 (t, J_{CF}=26.2 Hz), 137.8 ppm (m), no quat. C seen; mass spectrum gave M^+ 140.0246±0.0011 (8 ppm), calculated for $C_5H_4F_4$ 140.0249 dev.=0.0002 (1.9 ppm).

c. 24 mg (3.3%) of 109:[95] IR (gas phase) 3055, 1600, 1500, 1225, 845, and 575 cm^{-1}; ^1H NMR (CCl_4, 60 MHz) δ 3.15 (t of t, J_{HF}=11 Hz, J=3 Hz, 2H), 5.54 (m, 1H), 5.87 (m, 1H); ^{19}F NMR (CCl_4, 100 MHz) ϕ115.5 (br. s), 116.7 (t, J_{FH}=11 Hz).

d. 85 mg (11.67%) of 110: IR (gas phase) 1630, 1445, 1320, 890, 735, 480 and 415 cm^{-1}; ^1H NMR (CCl_4, 60 MHz) δ 6.45 (t, J_{HF}=11Hz, 1H), 1.92 ppm (br. s, 3H); ^{19}F NMR (CCl_4, 100 MHz) ϕ 111.97 (m, 2F0, 117.6 ppm (m, 2F); ^{13}C NMR (CCl_4, 300 MHz) δ 9.6 (s, CH_3), 120 (complex t's, J_{CF}=290 Hz, CF_2's), 136 (m, C_2), 154 ppm (m, C_1).

e. 73 mg (10.02%) of 111: λmax 254 nm; IR (gas phase) 1715, 1230, 1300, 1100, 910, 810 and 575 cm^{-1}; ^1H NMR (CCl_4, 60 MHz) δ 4.88 (d of m, J_{HF}=26 Hz, 1H), 1.8 ppm (quart. J=3 Hz, 3H); ^{19}D NMR (CCl_4, 100 MHz) ϕ 84, 85.7, 91.5, 94.5 ppm (all complex

m's); mass spectrum gave M^+ 140.0238±0.0015 (11.2 ppm), Cald. for $C_5H_4F_4$ 140.0249 dev.=0.0011 (7.4 ppm). The combined yield of isolated products was 34.58%. Order of elution was 111, 109, 110, 107 then 108. The GC relative yields were 26.0% for 107, 11.1% for 108, 6.5% for 109, 21.7% for 110 and 34.5% for 111.

Photolysis of Pyrazoline 106

2,2,3,3-Tetrafluorobicyclo[2.1.0]pentane, 107 and 3,3,4,4-tetrafluorocyclopent-1-ene 108.

Photolysis of 114.7 mg (0.68 mmoles) pyrazoline 106 in a 600 mL gas sample bulb (vycor) in vacu for 15 hours using a Rayonet photoreactor (350 nm) gave a crude photolysis mixture which was subjected to prep GC (20 ft. by 1/4 in. in 10% DNP at 60°C, 30 mL/min.) to give 30.7 mg (0.000 219 moles) 32% of 106, identical to the one obtained from pyrolysis of pyrazoline 106. It also gave 23.8 mg (.0001706 moles) 25% of 108; identical to the one obtained by thermolysis of 106.

The combined yield of isolated products was 57% and the relative GC yields were 56 and 44% for 107 and 108 respectively.

Photolysis of 107

Photolysis of 0.05 g (0.0035 mmoles) of 107 under the same conditions as for 106 failed to indicate the presence of any appreciable amount of 108. Spectral analyses indicated the presence of starting material 107.

1,2-Dideutero-3,3,4,4-tetrafluorocyclobutene 112

A 15 g (0.1 mole) hexafluorocyclobutene was treated with 5 g (0.119 moles) of lithium aluminum deuteride (98 atom % D, Aldrich Chemical) in identical procedure as for the synthesis of 45 using D_2O instead of H_2O. The product 2 g (0.0156 moles) was distilled as a colorless liquid b.p=55°C: IR (neat film) 2980 (s), 2880 (w), 2480 (s), 2360, 2300, 2140, 2040, 1600, 1500, 940, 810, 700, 650 (s), and 480 (s) cm^{-1}; ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 111.105 (s); ^{13}C NMR ($CDCl_3$, 300 MH z) δ 123.451 (t of t of m, $^1J_{C-F_2}$ = 287.87 Hz, $^2J_{C-F}$=28.21 Hz), 143.279 (m, 13 lines).

1,5-Dideutero-6,6,7,7-tetrafluoro-2,3-diazabicyclo[3.2.0]-hept-2-ene 106D

An ethereal solution of diazomethane (prepared from 3.12 g (0.0156 moles) of N-methyl N-nitroso-p-toluenesulfonamid) was added to 2 g (0.0156 mole) of 1,2-dideutero-3,3,4,4-tetrafluorocyclobutene in an identical procedure to 106 syntehsis to give 1.86 g (0.0109 mole) of 106D (70.1%): IR (neat film) 2960, 1450, 1350, 1260, 1100, 1000, 800 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 4.95 ppm (midpoint AB, J_{AB}=20 Hz, $\Delta\nu$=19.6 Hz).

Thermolysis of Pyrazoline 106D

1,4-Dideuter-3,3,4,4-tetrafluorobicyclo[2.1.0]pentane 107D, 1,3-dideutero-4,4,5,5-tetrafluorocyclopent-1-ene 108D, 1,1-dideutero-2-(methylene)-3,3,4,4-tetrafluorocyclobutane 109D, 1-deutero-2-(deuteromethyl)-3,3,4,4-tetrafluorocyclobutene 110D, and 2-deutero-3-(deuteromethyl)-1,1,4,4-tetrafluoro-1,3-butadiene 111D.

Identical procedure was followed as described for thermolysis of pyrazoline 106 but at 348°C. Starting with 0.9 g (0.0052 mole) of pyrazoline 106D, 0.66 g (87.7%) crude liquid pyrolysate was collected. The products were isolated by prep GC (20 ft by 1/4 in. in 10% DNP at 55°C, 33 mL/min) to give

a. 90 mg (12.18% of 107D: ^{1}H NMR (CCl_4, 300 MHz) δ 1.36 (br. m, J=0.93 Hz, 1H), 1.39 ppm (br. d, J=6.5 Hz, 1H); ^{19}F NMR (CCl_4, 100 MHz) ϕ 116.77 (midpoint, AB, J_{AB}=209.4 Hz, $\Delta\nu$=1451.37 Hz); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 7.39 (t, J_{CF}=3.27 Hz, C_5), 21.8 (complex M, $C_{19}C_4$), 115.84 ppm (t, J_{CF}=285.78 Hz, C_{21}, C_3).

b. 78 mg (10.56%) of 108D: ^{1}H NMR ($CDCl_3$, 60 MHz) δ 3.0 (m, J=12 Hz, J=3 Hz, 1H), 6.56 ppm (br. s, 1H).

c. 44 mg (5.95%) of 109D: ^{1}H NMR (CCl_4, 60 MHz) δ 5.68 (br. s), 5.98 ppm (br. s)

d. 42 mg (5.68%) of 110D: ^{1}H NMR ($CDCl_3$, 60 MHz) δ 2.0 ppm (br. m)

e. 39 mg (5.28%) of 111D: ^{1}H NMR ($CDCl_3$, 60 MHz) δ 1.8 ppm br. m).

The combined yield of isolated products was 39.65%. Order of elution was 111D, 109D, 110D, 107D then 108D. The GC

relative yields were 38.5% for 107D, 27.8% for 108D, 5.8% for 109D, 17.6% for 110D and 10.3% for 111D.

4-Methyl-6,6,7,7-tetrafluoro-2,3-diazabicyclo[3.2.0]hept-2-ene 119

An ether solution of diazomethane (prepared from 9 g (0.0396 mole) N-ethyl-N-nitroso-p-toluenesulfonamide)[93b] was added to 2.5 g (0.0198 mole) 3,3,4,4-tetrafluorocyclobutene in an identical procedure to 106 synthesis to give, after 3 minutes at 5°C, 1.44 g (40%) of colorless liquid: m.p. ~ 15°C; IR (neat film) 2990, 1550, 1460, 1350, 1210, 1150, 910, 880, 780, 700 cm^{-1}; ^1H NMR ($CDCl_3$, 60 MHz) δ 1.45 (d, J=6 Hz, 3H), 2.8 (m, 1H), 5.28 (9, 1H), 5.8 ppm (br. d of t, J=8 Hz, 4 Hz, 1H0.

Thermolysis of 119

Exo-5-methyl-3,3,4,4-tetrafluorobicyclo[2.1.0]pentane 120, endo-5-methyl-3,3,4,4-tetrafluorobicyclo[2.1.0]pentane 121, 1-methyl-3,3,4,4-tetrafluorocyclopent-1-ene 122, and 1-ethyl-3,3,4,4-tetrafluorocyclobutene 123

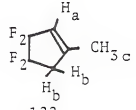
An identical procedure was employed as described for thermolysis of pyrazoline 106 but at 382°C. Starting with 0.97 g (0.0053 mole) of pyrazoline 119. A total of 0.75 g (0.0048 mole, 91%) crude liquid pyrolysate was collected. The products were isolated by prep GC (20 ft by 1/4 in. in 20% DNP at 55°C, 40 mL/min.) to give

a. 150 mg (19.64%) of 120: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.1 (d of t, $J_{CH_3\text{-}H(jem.)}$=6.15 Hz, $J_{CH_3\text{-}H(vic.)}$=1.13 Hz, $J_{CH_3\text{-}F}$=1.15 Hz, 3H) 1.559-1.787 (q, $J_{H\text{-}CH_3}$=6.26 Hz, $J_{H\text{-}H(vic.)}$=1.47 Hz, $J_{H\text{-}F}$=0.8 Hz, 1H), 2.28-2.36 ppm (d of t

of d, $J_{H-F(cis)}$=11.8Hz, $J_{h-H(vic.)}$=1.48 Hz, $J_{H-F(trans}$=3.75 Hz, 2H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 116.3 (midpoint, AB, J_{AB}=210.07 Hz, $\Delta\nu$=443.853 Hz, 4F, downfield F's virtual d J_{FH}=11.9 Hz, upfield F's br. s.) ^{13}C NMR ($CDCl_3$, 300 MHz) δ 13.858 (s, CH_3), 15.488 (t, J_{C-F_2}=2.68 Hz, C_5), 29.5 (q of m, J_{C-F_2}=31.4 Hz, C_1,C_4), 115.17 ppm (t, J_{C-F_2}=274.94 Hz, C_2,C_3; mass spectrum gave M^+-CH_3, 139.0173$\pm$0.0016 calculated for $C_5H_3F_4$ 139.0170 dev. 0.0002 (1.6 ppm).

b. 35 mg (4.58%) of 121: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.376 (d, $J_{CH_3-H(gem.)}$=6.87 Hz, 3H), 1.76 (sextet of triplet, $J_{H-CH_3(gem.)}$=6.87 Hz, $J_{H-H(vic.)}$=6.99 Hz, $^4J_{H-F}$=2.3 Hz, 1H), 2.52 ppm (m, $^3J_{H-F}$=9.67 Hz, $^3J_{H-H}$=6.96 Hz, $^3J_{H-F}$=3.6 Hz, 2H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 111.54 (midpoint, AB, J_{AB}=216.11 Hz, $\Delta\nu$=4726.04 Hz); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 11.49 (s, CH_3), 19.34 (t, $^3J_{C-F}$=3.84 Hz), 28.18 (d of d with fine splitting, $^2J_{C-F}$=32.52 Hz), 114.95 (t, $^1J_{C-F}$=264.15 Hz); mass spectrum gave M^+-CH_3, 139.0160$\pm$0.0006 calcd. for $C_5H_3F_4$ 139.0170, dev.=-0.0013 (-7.5 ppm).

c. 5 mg (0.66%) of 122: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.906 (t of m, $^5J_{CH_3-F}$=4.22 Hz, $^4J_{CH_3-H}$=1.48 Hz, $^4J_{CH_3-H_2}$=1 Hz), 2.835 (t of m, $^3J_{CH_2-F}$=11.62 Hz, $J_{CH_2-CH_3}$=1.16 Hz), 5.64 ppm (br. s. with fine splitting J_{H-F}=1.8 Hz, $^4J_{H-CH_3}$=1.53 Hz); Homonuclear proton decoupling of compound 122.



122

(1) irradiation of H_a changes CH_3 to a simple triplet J=4.22 Hz

(2) irradiation of H_b changes CH_3 to a simple triplet J=4.22 Hz and H_a to a br. s with fine splitting J=1-1.5 Hz

(3) irradiation of H_c changes H_b into triplet (J=11.62 Hz) of doublet (J=1.16 Hz).

^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 110.223 (br. s with fine splitting, $^3J_{F-H(vinylic)}$=1 Hz); 116.32 ppm (t of m, $^3J_{F-H_2}$= 11.6 Hz, $^4J_{F-H}$=1.28 Hz); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 17.844 (s, CH_3), 43.167 (t, CH_2, $^2J_{CH_2-F_2}$=25.71 Hz), 120.22 (t, 25.98 Hz), 121.48 (t, $^2J_{C-F}$=252.63 Hz), 149.9 ppm (complex multiplet, quaternary C).

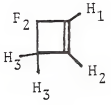
d. 200 mg (26.89%) of 123: ^1H NMR ($CDCl_3$, 300 MHz) δ 1.18 (t, $^3J_{H-H}$=7.47 Hz, 3H), 2.31 complex m, $^3J_{H-H}$=7.47 Hz, 2H), 6.43 ppm (t of p $^4J_{H-F}$=11.475 Hz, $^3J_{H-F}$=1.83 Hz, $^4J_{H-H}$=1.83 Hz, 1H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 111.68 (br. s with fine splitting), 116.09 ppm (d with fine splitting $^4J_{F-H}$=11.35 Hz); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 9.846 (S, CH_3), 18.273 (S, CH_2), 134.01-135.076 (m, $^2J_{C-F}$=14.2 Hz, $^3J_{C-F}$=10.44 Hz), 160.47 ppm (t, J= not obvious, quaternary carbon, weak). The combined yield of isolated products was 69.95%. Order of elution was 123, 120, 121, then 122. The GC relative yields were 25.93% for 122, and 40.34% for 123. The rest of the products tentatively assigned as 124 and 125 were in 25.24%, and 1.80% respectively.

1,1-Difluoro-1,3-butadiene 138

Identical procedure was followed as reported[72] in literature. The product obtained in 56% was purified by trap-to-trap distillation and separated in high purity by prep GC (20 ft by 1/4 in. in 20% DNP at 60°C, 30 mL/min): ^{1}H NMR ($CDCl_3$, 300 MHz) δ 4.92-5.21 (complex m, 3H), 6.2-6.33 ppm (complex m, 1H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 86.07 (d of d, $^{2}J_{FF}$=28.09 Hz, $^{3}J_{F-H}$=24 Hz), 88.59 ppm (d, J_{FF}=28.4 Hz).

3,3-Difluorocyclobutene 139 (by photolysis of 138)

Photolysis of 0.5 g (5.7 mmole) of 1,1-difluoro-1,3-butandiene in 20 g cyclohexane contained in a 60 mL quartz gas sample bulb with rotoflow teflon stopcock sealed in vacu for 4 days at 38°C using a Rayonet photoreactor (2537 Å) gave 10 mg (0.11 mmole) 1.9% of 3,3-difluorocyclobutene 139 which was isolated from the solution by prep GC (20 ft by 1/4 in. in 20% DNP at 80°C, 35 mL/min.): see the structure below.



^{1}H NMR ($CDCl_3$, 100 MHz) δ 3.03 (t of d of d, virtually as t of quartet, $^{3}J_{H_3-F}$=3.18 Hz, $^{3}J_{H_3-H_2}$=0.98 Hz, $^{4}J_{H_3-H_1}$=0.49 Hz, 2H), 6.126 (p of m, $^{3}J_{H_1-F}$=1.8 Hz, 1H), 6.705 ppm (t of d of t, $^{4}J_{H_2-F}$=14.4 Hz, $^{3}J_{H_2-H}$=2.19 Hz,

$^{3}J_{H_2-H_3}$=0.98 Hz, 1H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 104.52 ppm (d of t of d, $^{4}J_{F-H_2}$=14.21 Hz, $^{3}J_{F-H_3}$=3.1 Hz, $^{3}J_{F-H_1}$=1.84 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 45.17 (t, $^{2}J_{C-F}$=23.19 Hz), 134.16 (t, $^{2}J_{C-F}$=24.37 Hz), 142.74 ppm (t, $^{3}J_{C-F}$=17.09 Hz), no CF_2-carbon seen; mass spectrum m/e (rel. base %) 90, M^+ (2.5); 64, $M^+-C_2H_2$ (0.3); 26 $M^+-C_2H_2F_2$ (0.1), 59 (22), 45 (6), 31 (100), 29 (22).

2,2-Dichloro-3,3-difluorocyclobutanecarbonitrile 141

The title compound was prepared based on published method[69b,70c] as follows.

Into a 60 mL autoclave was introduced a 20 g (25 ml) (0.377 mole) acrylonitrile and 0.5 g hydroquinone, then 25 g (0.18 mole) of 1,1-dichloro-2,2-difluoroethylene was condensed in vacuum into the autoclave. The mixture was heated at 140-160°C for 20 hours. The above procedure was repeated for one more time. The combined crude product was distilled to give 72 g (0.38 mole) of 141: b.p. 57°C (17 mm); IR (neat film) 3035, 2960, 2255, 2235, 1725, 1615, 1420, 1350, 1300, 1150, 1040, 910, 790, 640, and 625 cm^{-1}; ^{1}H NMR (neat, 60 MHz) δ 2.7-3.4 (m, 2H), 3.6-4.1 ppm (m, 1H); ^{19}F NMR (neat, 60 MHz) ϕ 100.5 (midpoint AB, J_{AB}=200 Hz, downfield F's d of t J_{F-F}=200 Hz, $^{3}J_{F-H}$=8 Hz, highfield F,s d of t of d, J_{F-F}=200 Hz, $^{3}J_{F-H}$=14 Hz, J_{F-H}=3 Hz, $\Delta\nu$=480 Hz.

2,2-Dichloro-3,3-difluorocyclobutanecarboxylic acid 142, and 2-chloro-3,3-difluorocyclobutenecarboxylic acid 143

A mixture of 50 mL hydrochloric acid (38%) and 30 mL sulfuric acid (98%) was added into a 500 mL one-necked flask which had contained 75 g (0.389 mole) of 2,2-dichloro-3, 3-difluorocyclobutanecarbonitrile 141. The entire mixture as refluxed at 140°C for 9 hours. The mixture was neutralized with KOH/H_2O (40%) then the organic layer was extracted with ether and dried over anhydrous $CaCl_2$. The ether was distilled off the products to leave behind a yellow solid m.p. 90-100°C of 143 as the major product with a yellow liquid of 142 as minor. The total weight was 64 g (0.3809 mole) 97.6%. Spectral data of 142: ^1H NMR (neat, 60 MHz) δ 2.6-3.15 (m, 2H0, 3.4-3.95 (m, 1H), 11 ppm (s, 1H); ^{19}F NMR (neat, 60 MHz) ϕ 101 ppm (midpoint AB, J_{AB}=200 Hz, $\Delta\nu$=550 Hz, downfield F's, d of d of d, J_{F-F}=200 Hz, $^3J_{F-H}$=10 Hz, $^3J_{F-H}$=4 Hz, upfield F's, d of d of d of d, J_{F-F}=200 Hz, $^3J_{F-H}$=20 Hz, $^3J_{F-H}$=14 Hz, $^4J_{F-H}$=2 Hz.

The above mixture of 142 and mostly of 143 was stirred with excess KOH/H_2O (40%) for one hour at room temperature, then it was acidified with 38% HCl. The organic layer was extracted with ether which was distilled off to leave behind 62 g (0.369 mole) (94.8%) exclusively of 143: b.p. = 90°C (15 mm) ^1H NMR (neat, 60 MHz) δ 3.2 (t, $^3J_{H-F}$=3 Hz, 2H), 11 ppm (s, 1H); ^{19}F NMR (neat, 60 MHz) ϕ =114.5 ppm (t, $^3J_{F-H}$=3 Hz); mass spectrum gave M^+ 168.9784±0.0023, calculated for $C_5H_3O_2F_2Cl$ 168.9789 dev. 0.004 (2.9 ppm).

3,3-Difluorocyclobutanecarboxylic acid 144

A 1L bomb equipped with a gas inlet and outlet valves, and mechanical stirrer was charged with 62 g (0.369 mole) of 2-chloro-3,3-difluorocyclobutenecarboxylic acid, 400 mL methylenechloride and 1 g Pt/carbon. The bomb was purged with dry N_2-gas for 10 minutes then it was pressurized with H_2-gas up to 600 psi. The mixture was stirred at 60-80°C for one hour (exoergic reaction). The solvent was removed by simple distillation and the crude acid was distilled to give a colorless liquid b.p.=85-90°C (4-5 mm) which then solidified at 0°C to give 21.9 g, (0.161 mole, 43.6%) of needle like white crystals m.p. 48-50°C: IR (neat film) 3500-2500 (br.), 1680 cm^{-1}; ^1H NMR ($CDCl_3$, 300 MHz) δ 2.803-2.937 (complex m, 4H), 2.97-3.03 (complex m, 1H), 8 ppm (br. s, 1H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 90.84 ppm (midpoint, AB, J_{AB}=193.53 Hz, $\Delta\nu$=37.63.87 Hz, downfield F's, d of m J_{F-F}=193.53 Hz, $^4J_{F-H}$=3 Hz, upfield F's d of p with fine splitting J_{F-F}=193.53 Hz, J_{F-H}=14.4 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 26.6 (d of d, $^3J_{C-F}$=15 Hz, $^3J_{C-F}$=5 Hz), 39.0 (t, $^2J_{C-F}$=23 Hz), 118.7 (midpoint, AB, $^1J_{AB}$=270 Hz, $\Delta\nu$=91.24 Hz), 180.4 ppm (s, carbonyl C); mass spectrum, m/e (rel. base %) 136, M^+ (0.45); 91, M^+-CO_2H (9.6); 64, $M^+-CH_2CHCO_2H$ (100).

3,3-Difluorocyclobutene 139, (by oxidative decarboxylation of 144)

The synthesis of 139 was based on a published procedure.[76]

In a 100 mL 3-necked flask, equipped with a reflux condenser, which was connected to a trap kept at -78°C during

the reaction, and N_2-gas inlet stopcock, was introduced $Cu(OAc)_2.H_2O$ (0.1 g, 0.5 mmole), pyridine (1,16 g, 0.0147 mole) and 3,3-difluorocyclobutanecarboxylic acid (2.g,0.0147 mole) and 15 mL solvent (benzene or chlorobenzene). The mixture was stirred magentically for 40 minutes at room temperature. To the resulting homogeneous solution was added 97% Pb^{IV}tetraacetate (2.5 g, 5.7 mmole, must be recrystallized) and the remainder of the solvent (15 mL). The resulting mixture was stirred in dark for an additional hour at room temperature in dark then it was heated gradually up to 80°C and refluxed for one hour. The product was mostly condensed in the trap at -78°C, and more of the product was obtained by distilling it along with benzene. In case of chlorobenzene pentane or diethyl ether used to flush the product along with the distilled solvent. The total amount of the product obtained was 0.5 g (0.0055 mole, 37.7%) based on GC yield. The spectroscopic data are identical with the same product obtained from photolysis of 138.

1,1,2,2-Tetrachloro-3,3-difluorocyclobutane 146

This compound was prepared in identical procedure as was described for 141 from 100 g (0.751 mole) 1,1-dichloro-2,2-difluoroethylene and 70.1 g (60 mL, 0.73 mole) vinyledenechloride at 180°C for 9 hrs. to give 34 g (0.147 mmole) 20.1% of 146, a white solid: m.p. 53-55°C, b.p 60 (20 mm); ^1H NMR ($CDCl_3$, 60 MHz) δ 3.59 ppm (t, J_{H-F}=10 Hz); ^{19}F NMR (neat, 60 MHz) ϕ 101.5 ppm (t, J_{F-H}=10 Hz).

1,2-Dichloro-3,3-difluorocyclobutene 147

An identical procedure was followed as described for compound 101 using 29 g (0.126 mole) of 146 and 75 g (1.134 mole) zinc powder and 280 mL ethanol to give 11 g (0.0691 mole) 55% of 147 a colorless liquid b.p. 82-84.5°C: ^{1}H NMR (neat, 60 MHz) δ 3.2 ppm (t, J_{H-F}=3 Hz). ^{19}F NMR (neat, 60 MHz) ϕ 114 ppm (t, J_{F-H}=3 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ 48.5 (t, $^{2}J_{C-F}$=29 Hz), 116.8 (t, $^{1}J_{C-F}$=342 Hz), 122.5 (t, $^{2}J_{C-F}$=34.2 Hz), 136.8 ppm (t, $^{3}J_{C-F}$=29 Hz).

1-Chloro-4,4-difluorocyclobutene 148

Similar procedure was followed as described for 102. Using 3. g (0.0188 mole) of 147 and 0.75 g (0.0197 mole) lithium aluminum hydride in 100 mL ether to give 0.3 g (0.0024 mole) of 148: ^{1}H NMR (ether, 60 MHz) δ 2.66 (t, $^{3}J_{H-F}$=3 Hz), 6.3 ppm (t, $^{4}J_{H-F}$=13 Hz); ^{19}F NMR (ether, 60 MHz) ϕ =114 ppm (d of t, $^{4}J_{F-H}$=13 Hz, $^{3}J_{F-H}$=3.0 Hz).

1,1,2-Trichloro-3,3-difluorocyclobutane 150

Identical procedure was followed as described for 141. Using 26 g (0.264 mole) 1-chloro-2,2-difluoroethylene and 21.34 g (0.22 mole) vinledene chloride at 220°C for 22 hrs. gave 1.45 g (0.0074 mole) 3% of 150: colorless liquid b.p =80-84 (40 mm); ^{1}H NMR ($CDCl_3$, 60 MHz) δ 3.51 (d of d, midpoint AB, J_{AB}=6 Hz, Δν=16 Hz, 2H), 5.1 ppm (t of d, $^{3}J_{H-F}$=9 Hz, J_{H-F}=2 Hz, 1H); ^{19}F NMR ($CDCl_3$, 60 MHz) ϕ 102 (midpoint AB, J_{AB}=210 Hz, Δν=1410 Hz, upfield F's do of

octet, J_{F-F}=210 Hz, $^3J_{F-H}$=10 Hz, $^3J_{F-H}$=6 Hz, downfield F's d of sextet. J_{F-F}=210 Hz, J_{F-H}=10 Hz).

1-Chloro-3,3-difluorocyclobutene 151

Identical procedure was followed as described for 101. Using 1.4 g (0.0071 mole) of 150 with 4.3 g (0.064 mole) of powdered zinc in 30 mL ethanol gave 0.2 g (0.0016 mole) 22.6% of 151: ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 106.92 ppm (t of d, $^3J_{F-H}$=2.83 Hz, $^3J_{F-H(vinylic)}$=1.39 Hz).

3,3,Difluorocyclobutene 139 by reduction of 151

The reduction was achieved using an identical procedure as employed for 102 starting with 0.2 g (0.0016 mole) 151 and 0.8 g (0.021 mole) lithium aluminum hydride in 20 mL ether at room temperature for 22 hr. gave 139 with same spectral data as described before.

7,7-and 6,6-Difluoro-2,3-diazabicyclo[3.2.0]hept-2-ene 159 and 160

An ether solution of diazomethane (70 mL) was prepared from 7.14 g (0.0285 mole) N,N'-dimethyl-N,N'dinitrosotere-phthalamide which was mixed with 0.828 g (0.0111 mole) 3,3-difluorocyclobutene for 20 hrs. at room temperature following same technique as described for 106 synthesis to give 0.335 g (0.00372 mole) 33.5% of oily faint yellow liquid: IR (film) 2945, 1545 cm^{-1} (main peaks); ^1H NMR ($CDCl_3$, 60 MHz) δ 5.8 (m, 1H0, 5.2 (m, 1H, minor isomer) 4.6 (br. s with fine splitting, 2H), 1.5-2.9 (m, 3H0: ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 95.55 ppm (midpoint AB, major isomer 159,

J_{AB}=207.73 Hz, $\Delta\nu$=1055.48 Hz, upfield F's d of d of d of d J_{F-F}=207.73 Hz, J_{F-H}=20 Hz, J_{F-H}=10.5 Hz, J_{F-H}=4.51 Hz, downfield F's, do of d of d of d of d, J_{F-F}=207.73 Hz, J_{F-H}=18.99 Hz, J_{F-H}=9.99 Hz, J_{F-H}=3.42 Hz, J_{F-H}=1.79 Hz), 93.98 ppm (midpoint AB, minor isomer 160, J_{AB}=197.39 Hz, $\Delta\nu$=2486.46 Hz, upfiled F's d of d of d of d of d, J_{F-F}=197.39 Hz, $^3J_{F-H}$=21.26 Hz, $^3J_{F-H}$=11.11 Hz, $^4J_{F-H}$=4.34 Hz, downfield F's d of m, J_{F-F}=197.39 Hz, J_{F-H}=18.84 Hz, 14.94 Hz, 7.33 Hz and 4.86 Hz)

Thermolysis of 159 and 160

1,1-Difluoro-2-methyl-1,3-butadiene and 1,1-difluoro-3-methyl-1,3-butadiene, 161 and 162, 3,3-difluoro-1,4-pentadiene 163, 1-(methylene)-3,3-difluorocyclobutane 164 and 2,2-difluoro-1-vinylcyclopropane 169, 4,4-difluorocyclopent-1-ene 165, 3,3-difluorocyclopent-1-ene 166, and 1-fluorocyclopent-1-ene 167 and 2-fluorocyclopent-1-ene 168

A mixture of pyrazolines 159 and 160 (0.4 g, 0.00303 mole) was pyrolized following an identical technique as described for thermolysis of pyrazoline 106 over a period of 80 minutes at 350°C. A total of 99.22 mg (31.7%) of pyrolysate was collected. The products were isolated by prep GC (12 ft by 1/4 in. in 20% OV-210 at 55-60°C, 40 mL/min.) to give

a. 16.96 mg (17.09%) of 161 and 162: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 1.93 (d of d of d, virtual d of 9, J=4.24 Hz, 1.45 Hz and 0.86 Hz, CH_3 of 162), 2.75 (virtual triplet, J=8 Hz, CH_3 of 161),

4.82-4.91 (set of multiplets), 4.95-5.12 ppm (multiplet; ^{19}F NMR ($CDCl_3$m 300 MHz) ϕ 83.63 (d of d, J_{F-F}=34.22 Hz, $^3J_{F-H(trans)}$=28.91 Hz), 86.26 (d of d, J_{F-F}=34.76 Hz, $^3J_{F-H(cis)}$=4.14 Hz, of 162), 89.1 (d, J_{F-F}=46.02 Hz), 91.85 (d of d of t, J_{F-F}=46.02 Hz, J_{F-H}=24.8 Hz, J_{F-H}=1.8 Hz, of 161).

b. 27.56 mg (27.77%) of 163: ^{1}H NMR ($CDCl_3$, 100 MHz) δ 5.28 ppm (complex multiplet); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 96.473 ppm (t of t of t, $^3J_{F-H}$=9.7 Hz, $^4J_{F-H}$=2.67 Hz, $^4J_{F-H}$=0.63 Hz); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 117.83 (t, $^1J_{C-F}$=234.53 Hz), 120.01 (t, $^3J_{C-F}$=9.16 Hz), 132.457 ppm (t, $^2J_{C-F}$=29.19 Hz).

c. 15.9 mg (16.02%) of 164: ^{1}H NMR ($CDCl_3$, 300 MHz) δ 3.211 (t of t, $^3J_{H-F}$=11.94 Hz, $^4J_{H-H}$=2.45 Hz, 4H), 5.10 ppm (P, $^4J_{H-F}$=2.51 Hz, 2H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 95.62 (P, $^3J_{F-H}$=11.93 Hz); ^{13}C NMR ($CDCl_3$, 300 MHz) δ 44.79 (t, $^2J_{C-F}$=24.77 Hz, C_2), 110.48 (t, $^4J_{C-F}$=6.43 Hz), 117.45 ppm (t, $^1J_{C-F}$=176.75 Hz) quaternary C not seen. The spectrum contained also 0.36 mg (0.363%) of 169 whose spectra were identical with the published data.[80]

d. 5.6 mg (5.64%) of 165 and 8.4 mg (8.46%) of 166: ^{1}H, ^{19}F and ^{13}C NMR spectra were exactly identical and consistent with the published data.[86]

e. 24.44 mg (24.63%) of 167: ^{1}H NMR ($CDCl_3$, 60 MHz) δ 2.81 (d, $^3J_{H-F}$=6 Hz, 2H), 5.6 (br. s with fine splitting, 1H), 6.45 ppm (br. s. 2H); ^{19}F NMR ($CDCl_3$, 300 MHz) ϕ 127.94

(t of d of d of d, J_t=6.0 Hz, $J_{d's}$=4.6 Hz, 2.5 Hz and 0.2 Hz). A minor peak at ϕ 124 was assigned for 168; ^{13}C NMR ($CDCl_3$, 300 MHz) δ 36.60 (d, $^2J_{C-F}$=8.88 Hz), 103.37 (d, $^3J_{C-F}$=9.46 Hz), 126.78 (d, $^2J_{C-F}$=28.11 Hz), 134.66 (d, $^4J_{C-F}$=6.53 Hz), 163.01 ppm (d, $^1J_{C-F}$=268.31 Hz). Contains also 2 peaks assigned for the minor isomer 168: δ 37.147 (d, $^3J_{C-F}$=20.15 Hz), 121.45 ppm ($^3J_{C-F}$=8.21 Hz). The combined yield of isolated product was 31.7%. Order of elution was 161, 162; 163; 164, 169; 167, 168; 165; then 166.

Thermolysis of pyrazolines 159 and 160 at 205°C

Same procedure was followed as described for the thermolysis at 350°C and resulted in recovery of both 159 and 160.

Thermolysis of pyrazolines 159 and 160 at 288.7°C

Identical procedure was followed as described for the thermolysis at 350°C using 0.15 g (0.00113 mole) of the pyrazolines at 288.7°C. A total of 65.22 mg (55.2%) of pyrolysate was collected. The products were isolated by prep GC to give:

15.9 mg (24.37%) of 161 and 162

20.14 mg (30.87%) of 163

5.3 mg (8.12%) of 164 and 169

5.328 mg (8.16%) of 165

8.48 mg (12.99%) of 166

7.95 mg (12.16%) of 167 and 168

The combined yield of isolated products was 55.2%.

Attempted synthesis of 2,2-difluorobicyclo[2.1.0]pentane-131 (by CH_2N_2/CuCl)

The following procedure was adapted after that of Pincock, Chesick and Roth.[83a] A mixture of 3,3-difluorocyclobutene (1.0 g, 0.0111 mole) and pentane (or ether) was transferred into an ice-cooled 3-necked flask (no ground joints) contained 0.3 g CuCl and equipped with a glass tube, as a gas inlet for CH_2N_2 reached near the bottom of the solution, a thermometer and a dry ice condenser connected to a long tygon tube reached the back of the hood cupord served as excess gas outlet. The inlet tube into the 3-necked flask was connected to the CH_2N_2 generator which consisted of a 250 mL 3-necked flask (no ground joints) equipped with a tube for N_2-gas inlet and a stopcock where N,N'-dimethyl-N,N'-dinitrosoterephthalamide was added in one gram lots every 15 minutes onto a 50 mL of 50% NaOH with 40 mL decaline to dissolve CH_2N_2. A total of 29 g of the amide was used. The reaction was monitered by GC using 12 ft by 1/4 in. in 20% OV-210 at 25°C, 30 mL/min. After 3 hrs. no product was detected by GC then $Cu(acac)_2$ (0.3 g) was added and continued CH_2N_2 addition to complete 7 hours. The reaction solution was transferred into a 50 mL one-necked flash using vacuum line and GC analysis and spectral data indicated the recovery of starting material. The off white CuCl turned gradually into green and ultimately into dark solid.

Attempted synthesis of 2,2-difluorobicyclo[2.1.0]pentane 131 (by Et_2Zn and CH_2I_2)

A similar procedure was followed after that of Nishimura and others[83b,c] as follows. A 50 mL 3-necked flask equipped with a constant pressure addition funnel mounted with a nitrogen inlet rubber septum, dry ice condenser, magnetic stirrer bar and a rubber septum. The outlet of the condenser was connected to a mineral oil U-tube bubbler. The glassware used for the apparatus was dried in an 120°C oven and assembled hot, then cooled to ambient temperature under a slow flow of dry nitrogen. The N_2 flow was discontinued and with standard syringe technique[94a] the following reagent were placed in the reaction flask: 18 mL 1.6 M diethyl zinc[94b] in toluene (29 mmole, Aldrich, caution! extremely pyrophobic), 0.745 g (0.0082 mole) 3,3-difluorocyclobutene in pentane and 7.76 g (29 mmole) CH_2I_2 which was added dropwise within 15 minutes. The condenser was filled with dry ice prior to addition of reagents and the reaction mixture was magnetically stirred. Reaction progress was monitored by anaerobically syringing out a small sample of the mixture into a septum-capped NMR tube and examining it by ^{19}F NMR for disappearance of the olefin (ϕ=104.5, J=14 H_2). The sample could then be placed back into the reaction mixture. No product formation was observed to occur at room temperature for 7 hours. The reaction mixture was then heated to 80°C and continued for 8 hours, which again analysis indicated same negative result and

even when same procedure was repeated using neat diethyl zinc.[94b] The reaction flask was cooled to 0°C and the mixture is slowly quenched (caution!) with approximately 20 mL of 0.75 M HCl and transferred to a separatory funnel. The organic layer was washed twice with 0.75 M HCl and twice with distilled water then dried over $CaCl_2$. The resulting solution was examined by ^{19}F NMR which indicated the presence of only the starting material. GC analysis indicated the presence of 3-new products which were isolated by prep GC (12 ft by 1/4 in. in 20% OV-210 at 70°C, 30 mL/min.) to give $CH_3(CH_2)_nI$, n=2,3.

a. CH_3CH_2I: ^1H NMR ($CDCl_3$, 60 MHZ) δ 1.25 (t, J_{H-H}=8 Hz), 2.15 (Sextet, J_{H-H}=8Hz J_{H-H}=6 Hz), 3.5 (t, J=6Hz; ^{19}F NMR ($CDCl_3$, 60 MHz) No signal.

b. $CH_3CH_2CH_2I$($CDCl_3$, 60 MHz) δ 1.0(quartet, J=6 Hz), 1.2-2.1 (m, J=8 Hz, 6 Hz, and 4 Hz), 3.25 ppm (t, J=6 Hz); ^{13}C NMR ($CDCl_3$, 100 MHz) δ =7.7 (s),14.0 (s), 24.24 (s), 35.99 ppm (s).

Kinetics and Thermodynamics

Thermolysis of 2,2,3,3-tetrafluorobicyclo[2.1.0]pentane 107 in the Gas Phase

The thermolysis of 107 was carried out in a well-conditioned, spherical pyrex vessel of approximately 200 mL capacity connected to a standard high-vacuum line. The vessel is submerged in a stirred, thermostated, molten salt bath (eutectic mixture 50/50 by weight of $NaNO_2$ and KNO_3,

m.p. $\simeq$ 150°C). The temperature was measured using a chromel-alumel thermocouple in conjunction with a Tinsley type 3387E potentiometer. The thermocopule was immersed in a well next to the thermolysis vessel. The temperature was controlled to $\pm$0.1°C using a Hallikainen (now TOTCO) Instrument Thermotrol Proportional controller with a model 1256Z platinum resistance probe. For kinetics a 10-20 mm of pure sample of 107 was expanded into the thermolysis vessel. The kinetics run was sampled at convenient intervals by removing small fractions of the pyrolysis mixture by expansion through a small section of the vacuum line into a gas bulb and diluting with argon. This sample bulb was removed and used to make multiple GC injections for ratio analysis using a gas chromatograph equipped with gas injection valve. A Hewlett-Packard gas chromatograph with a flame ionization detector was used in conjunction with Hewlett-Packard integrator for analysis. Baseline resolution of peaks was observed. Each point in the rate constant is an average of at least 3 GC runs, values were taken for the peak integration. The rate constant plot contained six point and was derived by a linear least squares analysis of the experimental data yielding a correlation coefficient of 0.99998-0.9995. The column was 10 ft. by 1/8 in. in 10% TCP at 55°C, 8 mL/min. The products were identified by comparing retention time with authentic samples. Rate data were measured for six different temperatures in the range of 334.5-364.5°C. Appendix B.

Isomerization of endo-5-methyl-2,2,3,3-tetrafluoro-bicyclo[2.1.0]pentane 121

The gas phase isomerization of 121 to 120 was carried out as described for that of 107 above except GC analyses were performed using the Hewlett-Packard 5790A series gas chromatograph in conjunction with HP-3390A integrator. The column was 20 ft by 1/8 in. in 10% DEGS at 80°C, 4 mL/min. Rate data were measured at six different temperatures in the range of 209-243°C. Appendix B.

Equilibrium of 120 and 121 in the Gas Phase

Into a well conditioned thermolysis vessel at the indicated temperatures was expanded 6-20 mm of exo-5-methyl-2,2,3,3-tetrafluorobicyclo[2.1.0]pentane 120 and rate constant were measured as was described for 107; using 20 ft by 1/8 in. in 10% DEGS at 80°C, 4 mL/min. Kinetics and equilibrium ratios were obtained after 20 half lives. The results for the equilibrium constants K=121/120 are presented in table 5-1 below. Each ratio is an average of at least three analyses.

Table 5-1. Equilibrium Constants for 120 and 121 in the Gas Phase

Temp. °C	K
262.5	0.0662
257.0	0.0641
250.0	0.0622
243.0	0.0607
236.25	0.0586
230.0	0.0578
223.5	0.0556
217.0	0.0531

Rearrangement of 120 to 122 in the Gas Phase

Into a well conditioned thermolysis vessel at 358°C was expanded 20 mm of exo-5-methyl-2,2,3,3-tetrafluorobicyclo-[2.1.0]pentane (120) and rate constant was measured as was described for 107, using 20 ft by 1/8 in. in 10% DEGS at 85°C, 12 mL/min. The result of rate consant is presented below.

$$k=2.68 \times 10^{-4}\ s^{-1} \text{ at } 358\ ^{\circ}C$$

Equilibrium of 45 to 46 in the Gas Phase

Into a well-conditioned vessle at the indicated temperature was expanded 50 mm of 3,3,4,4-tetrafluorocyclobutene 45. The isomerization to 46 was monitored as was described for 107 except the HP 33805 integrator was used. The rate was measured at one temperature and the equilibrium ratios were determined by GC analysis (20 ft x 1/8 in. in 10% DNP at 80°C and 12 mL/min) after 20 half lives. The equilibrium ratio

is the average of three analyses as indicated below

Temp.°C	K
315.0	77.5

Equilibrium of 110 to 111 in the Gas Phase

The rate constant and equilibrium constant were determined in analogous manner as described for 45 above. Results are lised below.

Temp.°C	K
315.0	0.505

The equilibrium was tested starting from 111 to 110 as described above. The data are given below

Temp.°C	K
315.0	2.01

Equilibrium of 123 to 124 in the Gas Phase

The data listed below were determined as was described for 45.

Temp.°C	K
315	0.241

Equilibrium of 139 to 138 in the Gas Phase

The data are given below and were determined as was described for 45

Temp.°C	K
237	>945

CHAPTER 6
GENERAL CONCLUSIONS

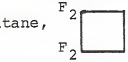
The thermal rearrangement of 2,2,3,3-tetrafluorobicyclo[2.1.0]pentane (107) to 3,3,4,4-tetrafluorocyclopentene required an additional 7.6 kcal/mol relative to the hydrocarbon due to the presence of four fluorine atoms.

Although 107 was prepared by thermal deazetation of its corresponding pyrazoline 106, attempted synthesis of 2,2-difluorobicyclo[2.1.0]pentane in analogous manner did not succeed.

The study of conrotatory ring opening of 1-methyl-3,3,4,4-tetrafluorocyclobutene (110) to 2-methyl-1,1,4,4-tetrafluoro-1,3-butadiene (111) indicated that the cyclic isomer was thermodynamically preferred with an equilibrium value of 0.5 as compared with a value of 77.5 for the system without the methyl group.

APPENDIX A

Calculated ΔH_f°, from group equivalent values and strain energy, for 1,1,2-2-tetrafluorocyclobutane ring.

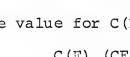
The group equivalent values needed for tetrafluorocyclobutane,  , are

1. $2[C(F)_2\ C(CF_2)]$
2. $2[C(H)_2\ C(CF_2)]$

Unfortunately no value has been assigned for either of the above group but an approximation can be made by extrapolating their values from other known group values

the value for $C(F)_2C_2$= -104.9[8] kcal/mol and

$C(F)_2(CF_2)_2$= -95.8 kcal/mol

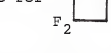
If one were to assume that $C(F)_2 \cdot C(CF_2)$ group equivalent value is the average of $C(F)_2\ C_2$ and $C(F)_2(CF_2)_2$ then the value for $C(F)_2\ C(CF_2)$= -100.35 kcal/mol. Applying a similar approximation for the group value $C(H)_2C(CF_2)$ [average of $(CH)_2C_2$(-4.9 kcal/mol) and $C(H)_2(CF_2)_2$(-103.5 kcal/mol)] resulted in a value of -59.22 kcal/mol which led to Es of  =107.14 an unplausible value. Therefore different

approximation was followed. If we assume that in going from

$C(F)_2C_2(-104.9)$ to $C(F)_2(CF_2)_2(-95.8)$

an additional four fluorine atoms added 9.1 kcal/mol (destabilization derived from perfluorocyclopropane) incremental destabilization or 2.275 kcal/mol per one F-atom then if we assume

$$C(H)_2\ C(CF_2) \cong C(H)_2\ C_2 + F_2$$
$$= -4.95 + (-2x2.275)^*$$
$$= -9.5 \text{ kcal/mol}$$

then the group value for  will be

$$2[C(F)_2\ C(CF_2)] + 2[C(H)_2\ C(CF_2)]$$
$$= 2[-100.35) + 2\ [-9.5[= -219.7 \text{ kcal/mol.}$$

Since experimental ΔH_f^o for equal -202 kcal/mol, then

$$Es^{**} = (-202)-(-219.7) = 17.7 \text{ kcal/mol}$$

---

* Negative sign indicates substitution by fluorine on cyclobutane ring must be stabilizing.

** The ring strain (Es) of a cyclic molecule is conventionally defined as the difference between its experimental ΔH_f^o and that for its corresponding hypothetically strain free ring, calculated from thermodynamical bond energies or group values. By this definition the Es of cyclopropane ($C\text{-}C_3H_6$) and cyclobutane ($C\text{-}C_4H_8$) are 27.5 and 26.5 kcal/mol, respectively.[96]

APPENDIX B
KINETIC DATA

Table B-1. Kinetic Data for Thermal Rearrangement of 107 to 108 at 334.5°C

min	%107	%108
5.0	96.73	1.0
	97.59	0.9
	97.59	1.08
60.0	89.14	9.28
	86.3	9.14
	87.6	9.16
120.0	81.45	17.13
	80.66	16.95
	81.18	17.23
180.0	72.52	23.78
	73.32	23.42
	72.68	23.54
240.0	67.84	30.08
	67.09	29.7
	64.71	29.15
	64.88	28.82
370.0	54.57	42.04
	54.26	40.92
	54.79	41.7
	52.17	39.51
484.0	46.84	50.45
	45.72	49.09
	45.99	48.57
	44.11	46.80
540.0	43.13	53.71
	42.92	53.2
	42.71	53.18
	41.5	50.92

Table B-2. Kinetic Data for Thermal Rearrangement of 107 to 108 at 340.0°C

min	%107	%108	%118	%std
30.0	70.21	5.68	0.10	23.31
	69.68	5.63	0.26	23.16
	69.68	5.69	0.10	23.28
60.0	64.91	10.68	0.11	23.71
	64.09	10.47	0.5	23.76
	64.3	10.72	0.17	24.52
90.0	60.27	15.28	0.17	24.09
	58.77	14.73	-	24.31
	57.81	14.37	-	23.78
	57.64	14.2	-	23.71
120.0	56.01	19.26	0.11	24.31
	55.52	18.93	0.14	24.27
	55.41	18.93	-	24.28
160.0	47.69	22.72	0.10	24.31
	48.42	23.24	0.5	25.01
	48.12	22.97	-	26.22
240.0	38.97	30.38	-	26.29
	38.38	29.97	-	27.08
	37.73	29.38	-	28.78
365	27.67	38.79	-	27.66
	27.47	37.79	-	27.73
	28.85	40.61	-	27.57

Table B-3. Kinetic Data for Thermal Rearrangement of 107 to 108 and 118 at 346.0°C

min	%107	%108	%118	%std
20.0	69.59	5.67	0.30	23.46
	69.02	5.73	0.21	23.67
	68.21	5.82	0.25	24.40
50.0	61.44	12.79	0.60	23.99
	60.57	12.67	0.56	23.73
	61.23	12.98	0.61	23.83
70.0	56.11	17.06	0.77	23.38
	56.44	16.83	0.81	24.64
	57.13	16.97	0.82	23.6
100.0	50.35	22.45	1.05	23.84
	49.59	22.33	0.86	25.06
	48.67	22.51	0.97	25.16
120.0	46.77	26.22	1.07	23.87
	46.31	26.23	0.88	23.84
	46.65	25.78	-	24.63
152.0	40.86	30.29	1.36	24.34
	40.39	30.13	1.41	24.45
	40.93	30.13	-	25.14
210.0	31.41	34.54	1.69	26.68
	32.04	36.32	-	25.13
	31.04	35.22	0.90	26.73

Table B-4. Kinetic Data for Thermal Rearrangement of 107 to 108 at 352.0°C

min	%107	%108	%118	%std
22.0	61.29	7.95	-	27.35
	63.45	8.54	-	26.84
	62.37	8.46	0.40	27.19
40.0	56.24	13.82	0.77	27.29
	57.78	14.22	-	26.92
	56.97	14.09	0.24	27.39
60.0	51.65	19.95	0.27	27.12
	51.77	19.87	-	27.27
	51.59	19.65	0.29	27.73
80.0	45.97	24.23	-	28.0
	43.42	23.61	0.73	28.91
	45.33	24.11	0.2	28.36
100.0	39.06	26.98	1.0	29.81
	38.04	26.74	0.35	29.63
	39.68	27.96	-	29.33
120.0	34.66	30.54	0.31	29.71
	36.18	31.27	-	29.31
	35.18	30.46	-	29.88
150.0	30.77	36.34	-	29.50
	30.43	35.72	-	30.28
	30.57	36.21	-	30.93

Table B-5. Kinetic Data for Thermal Rearrangement of 107 to 108 at 358.0°C

min	%107	%108	%118	%std
15.0	64.16	8.82	0.13	21.15
	66.72	9.17	0.05	23.1
	66.21	9.00	-	22.48
30.0	59.74	16.51	0.22	22.51
	58.941	16.94	-	22.9
	57.93	16.58	0.23	23.0
	53.79	14.30	-	25.61
40.0	54.67	21.18	-	22.70
	54.80	21.18	-	23.35
	53.10	20.38	-	23.74
50.0	47.65	23.90	-	24.65
	46.99	26.36	-	22.23
	48.63	24.35	-	23.37
60.0	45.66	28.76	-	23.33
	45.34	28.86	-	22.96
	42.4	27.26	-	24.86
70.0	41.66	32.43	-	23.26
	37.25	32.7	-	22.56
	42.57	31.45	-	23.26
	38.97	26.14	-	24.16
90.0	35.59	38.77	-	23.83
	35.60	38.93	-	23.34
	35.89	37.69	-	24.81

Table B-6. Kinetic Data for Thermal Rearrangement of 107 to 108 at 364.5°C

min	%107	%108	%118	%std
5.0	75.0	5.15	-	18.35
	74.69	5.20	-	18.51
	74.16	5.36	-	19.50
15.0	66.58	13.76	-	18.86
	62.54	13.23	-	21.19
	74.78	14.32	-	18.3
20.0	62.04	17.68	-	19.34
	59.45	17.35	-	19.13
	61.95	18.12	-	18.38
25.0	53.96	20.23	-	20.32
	56.66	21.13	-	18.87
	57.43	22.0	-	19.06
30.0	53.14	25.0	-	19.23
	52.62	24.77	-	19.02
	52.43	24.33	-	19.18
35.0	50.63	27.92	-	19.89
	48.39	27.33	-	19.34
	48.62	27.01	-	18.71
45.0	42.02	32.54	-	19.6
	44.09	32.14	-	20.49
	41.29	32.73	-	20.50

Table B-7. Kinetic Data for Thermal Isomerization of 121 to 120 at 209.0°C

min	%121	%120
35.6	85.89	6.44
	85.52	6.35
	85.73	6.38
70.6	80.18	11.73
	80.18	11.69
	79.90	11.74
105.6	75.28	16.95
	74.27	16.83
	75.08	17.03
145.6	69.79	22.64
	69.21	22.88
	68.96	23.38
185	64.31	28.28
	63.94	28.53
	63.67	28.57
225.0	59.36	32.44
	57.73	34.10
	59.13	33.24
265.0	55.27	36.92
	54.62	37.22
	55.09	37.14

Table B-8. Kinetic Data for Thermal Isomerization of 121 to 120 at 217.0°C

min	%121	%120
20.0	86.23	7.37
	86.18	7.38
	86.30	7.31
40.0	80.00	14.07
	80.29	13.91
	79.52	14.52
60.0	73.90	19.85
	73.29	19.77
	72.88	20.12
80.0	68.53	25.72
	68.45	25.24
	64.87	24.53
100.0	63.14	30.35
	63.15	30.58
	63.30	30.78
150.0	52.69	41.70
	52.09	42.12
	51.48	42.16

Table B-9. Kinetic Data for Thermal Isomerizaton of 121 to 120 at 223.5°C

min	%121	%120
20.0	78.54	11.54
	77.39	11.47
	78.50	11.58
40.0	69.16	20.63
	69.57	20.84
	69.32	20.84
60.0	61.11	28.19
	60.50	28.12
	58.84	27.42
75.0	54.98	33.72
	55.49	33.89
	55.61	34.10
93.0	50.32	40.36
	50.87	39.90
	50.45	39.81
115.0	45.04	46.54
	45.52	47.37

Table B-10. Kinetic Data for Thermal Isomerization of 121 to 120 at 230.25°C

min	%121	%120
15.0	69.26	18.07
	69.17	18.14
30.0	59.36	25.29
	58.47	26.87
	58.67	26.40
45.0	49.63	36.39
	49.84	36.66
	46.92	36.36
55.0	44.15	41.70
	42.62	41.47
	41.57	43.52
65.0	36.44	46.74
	39.91	45.86
	38.84	45.05
75.0	34.48	50.99
	34.80	51.63

Table B-11. Kinetic Data for Thermal Isomerization of 121 to 120 at 236.5°C

min	%121	%120
10.0	76.62	16.19
	77.14	15.83
	76.74	15.82
20.0	63.35	27.69
	64.83	28.37
	63.87	28.32
30.0	54.03	38.36
	53.85	38.33
	53.41	38.21
40.0	45.83	47.51
	45.90	47.68
	44.81	47.13
50.0	38.08	54.47
	38.06	54.12
	37.57	53.61
60.0	32.00	60.54
	32.16	60.30
	32.29	59.47

Table B-12. Kinetic Data for Thermal Isomerization of 121 to 120 at 243.0°C

min	%121	%120
3.0	83.07	8.20
	82.28	8.00
	82.26	8.22
6.0	76.39	15.47
	75.80	15.28
	76.10	15.18
9.0	69.94	21.14
	69.33	21.02
	70.41	21.53
12.0	63.821	26.57
	63.24	26.37
	63.71	27.01
15.0	58.82	32.39
	58.38	32.34
	58.93	32.83
18.0	56.08	38.65
	53.43	37.44
	52.63	38.00

Table B-13. Kinetic Data for the Equilibrium Constant for 120 and 121 at 217.0°C

hr	%120	%121
50.0	93.69	4.99
	94.08	4.99
	93.32	5.19
	93.46	5.26
	93.87	5.23

Table B-14. Kinetic Data for the Equilibrium Constant for 120 and 121 at 223.5°C

hr	%120	%121
35.0	93.92	5.26
	93.93	5.30
	94.00	5.20
	94.13	5.29
35.25	93.97	5.23
	93.84	5.28
	94.00	5.14
	94.16	5.04

Table B-15. Kinetic Data for the Equilibrium Constant for 120 and 121 at 230.0°C

hr	%120	%121
20.0	94.052	5.41
	93.93	5.51
20.761	93.602	5.34
	94.49	5.51

Table B-16. Kinetic Data for the Equilibrium Constant for 120 and 121 at 236.25°C

hr	%120	%121
11.75	93.79	5.35
	93.72	5.42
	93.61	5.55
	93.72	5.42
	93.71	5.42
12.75	93.53	5.62
	93.66	5.50
	93.72	5.44
13.66	93.37	5.58
	93.60	5.55
	93.72	5.49
	93.84	5.39

Table B-17. Kinetic Data for the Equilibrium Constant for 120 and 121 at 243.0°C

hr	%120	%121
6.6	93.64	5.72
	93.63	5.72
	93.70	5.69
	93.74	5.67
7.6	93.67	5.67
	93.58	5.69
	93.79	5.64

Table B-18. Kinetic Data for the Equilibrium Constant for 120 and 121 at 250.0°C

hr	%120	%121
5.0	93.36	5.86
	93.48	5.78
	93.46	5.80
	93.47	5.73
	93.47	5.81
6.0	93.32	5.89
	93.26	5.90
	93.42	5.78
	93.40	5.82
	93.43	5.78

Table B-19. Kinetic Data for the Equilibrium Constant for 120 and 121 at 257.0°C

hr	%120	%121
2.68	93.24	6.06
	93.17	6.05
	93.30	6.01
	93.22	6.02
3.68	93.31	5.89
	93.24	5.97
	93.26	5.97
	93.39	5.88

Table B-20. Kinetic Data for the Equilibrium Constant for 120 and 121 at 262.5°C

hr	%120	%121
1.83	93.18	6.16
	93.17	6.16
	93.02	6.11
	93.10	6.19
2.5	93.11	6.22
	93.15	6.13

Table B-21. Kinetic Data for Thermal Rearrangement of 120 to 122 at 358.0°C

min	%120	%122
15.0	70.16	21.77
	70.53	21.98
	71.27	21.51
30.0	54.52	39.42
	55.33	38.55
	5.04	38.88
45.0	42.21	51.00
	42.86	52.18
	43.96	50.94
55.0	37.94	57.46
	36.21	59.32
	36.69	58.91
65.0	31.65	64.31
75.0	28.81	67.01
	27.51	67.74
	28.24	67.07
85.0	25.31	71.20
	25.52	71.09
	27.25	69.30

Table B-22. Kinetic Data for Thermal Isomerization of 45 to 46 and Equilibrium Constant st 315.8°C

min	%45	%46
15.0	86.61	13.22
	86.54	13.28
	86.47	13.41
33.0	73.62	26.25
	73.49	26.37
	73.51	26.37
45.0	65.91	33.97
	65.89	33.87
	66.16	33.83
60.0	56.42	43.51
	55.71	44.28
	56.19	43.80
90.0	41.64	58.25
	41.36	58.49
	42.51	57.33
105.0	36.27	63.58
	35.53	64.36
1560.0	1.27	98.50
	1.26	98.54

Table B-23. Kinetic Data for Thermal Isomerization of 110 to 111 and Equilibrium Constant at 315°C

min	%110	%111
36.0	86.23	6.72
	86.42	6.89
	85.88	6.94
70.0	81.99	11.03
	82.64	11.86
	82.25	11.97
105.0	79.00	15.42
	79.08	15.69
160.0	75.17	20.08
	74.67	20.23
	74.21	20.60
200.0	72.88	22.40
	71.14	23.87
	71.84	23.75
230.0	70.10	24.97
	72.57	24.79
	68.52	25.71
	67.77	25.36
332.0	64.23	32.23
	64.92	31.73
1800.0	60.09	30.67

Table B-24. Kinetic Data for Thermal Isomerization of 111 to 110 and Equilibrium Constant at 325°C

min	%111	%110
60.0	72.33	15.78
	74.70	15.12
	78.02	14.17
140.0	59.71	31.67
	58.38	31.40
	61.04	32.04
	61.99	30.59
181.0	54.77	39.00
	55.49	37.59
235.0	47.31	43.14
	47.88	41.71
	48.01	43.63
360.0	40.25	48.89
	38.54	50.32
	39.06	49.57
630.0	31.42	53.18
	35.82	65.18
	30.37	58.53
1375.0	23.71	50.58
	34.32	65.68
	27.40	54.77
1754.0	22.29	44.59

Table B-25. Kinetic Data for Thermal Isomerization of 123 to 124 and Equilibrium Constant at 314.75°C

min	%123	%124
10.0	89.11	1.48
	87.77	1.33
	86.06	1.28
20.0	87.03	2.58
	88.13	2.60
	87.98	2.61
30.0	86.06	3.68
	87.53	3.78
40.0	86.57	4.85
	86.12	4.72
	86.11	4.77
50.0	85.74	5.81
	85.74	5.87
	85.44	5.88
60.0	84.67	6.80
	84.28	6.74
	84.66	6.87
420.0	76.07	16.14
	76.16	16.44
	75.69	16.39
1370.0	76.62	17.94
	76.98	18.54
	76.5	18.56
1610.0	77.00	18.46
	77.45	18.41
	78.85	20.03

APPENDIX C
SELECTED SPECTRA

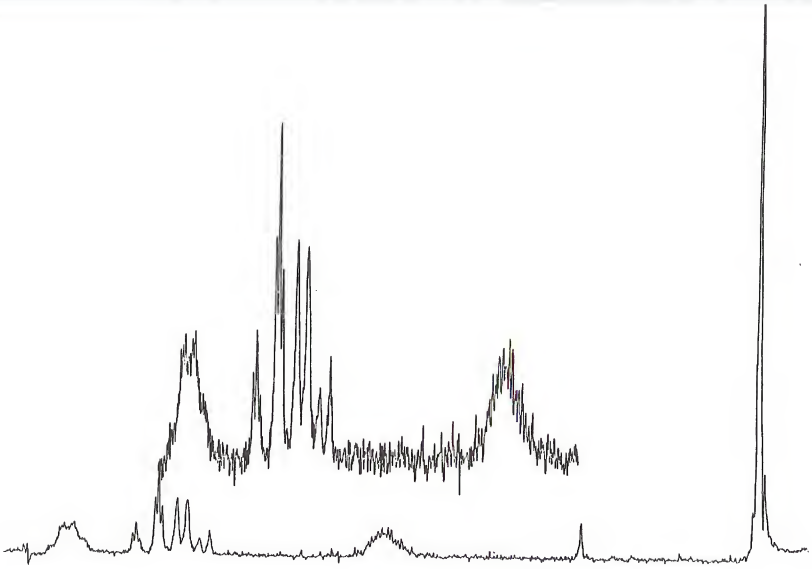


Figure C-1. ^{1}H NMR Spectrum of 106.

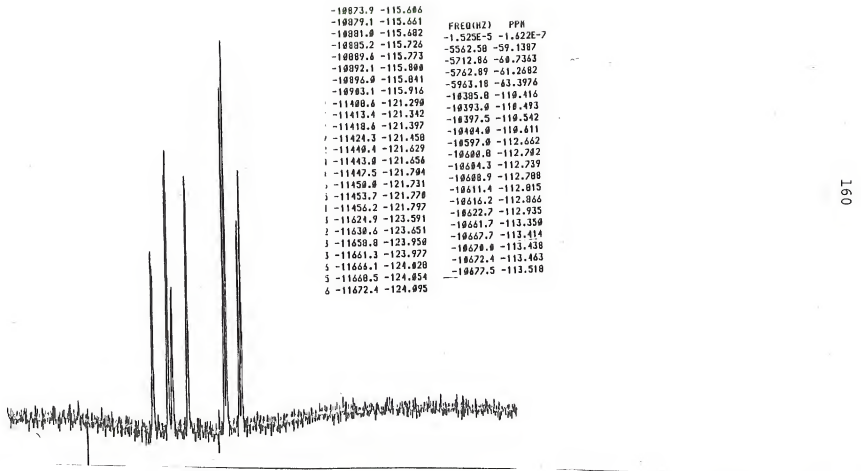


Figure C-2. ^{19}F NMR Spectrum of 106. (See Figure C-3 for expansion)

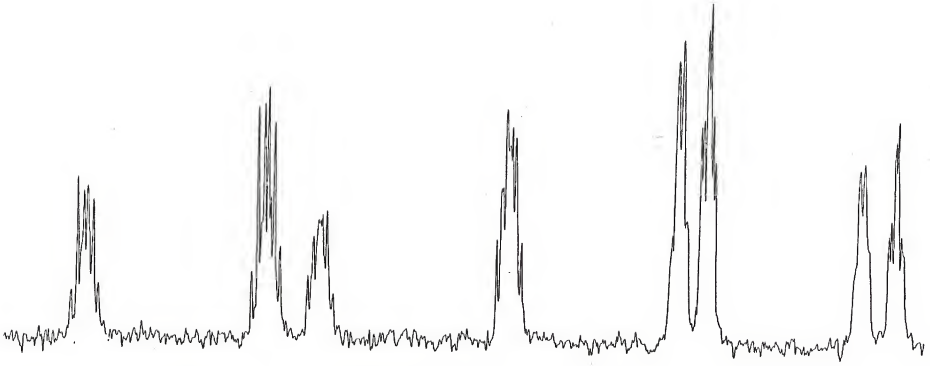


Figure C-3. Expansion of Figure C-2.

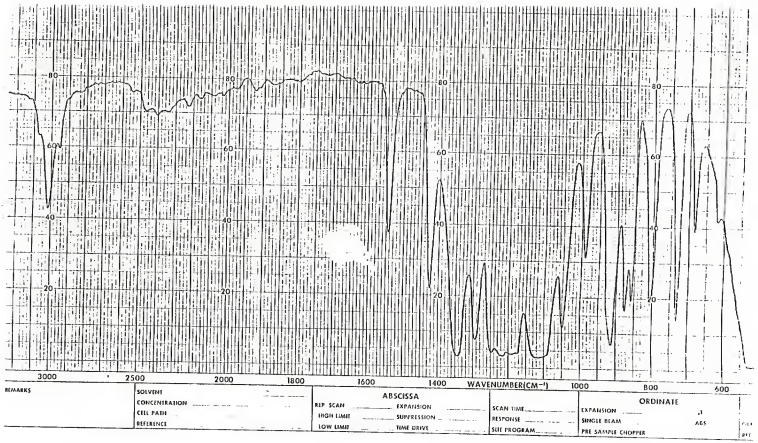


Figure C-4. I.R. Spectrum of 106.

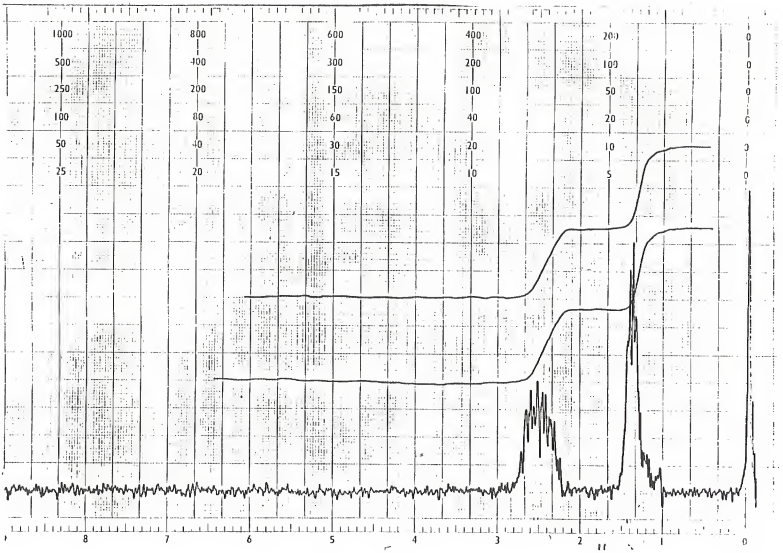


Figure C-5. ^{1}H NMR Spectrum of 107.

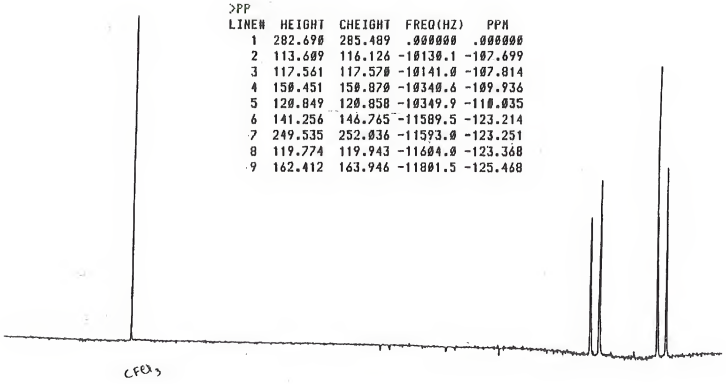


Figure C-6. ^{19}F NMR Spectrum of 107.

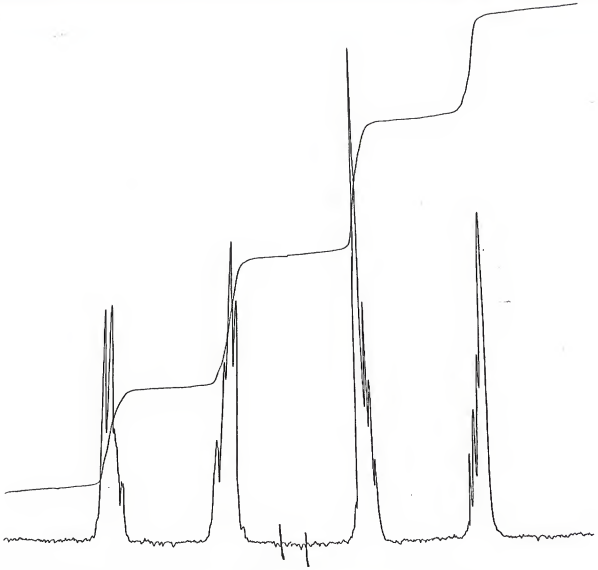


Figure C-7. Expansion of ^{19}F NMR Spectrum of 107.

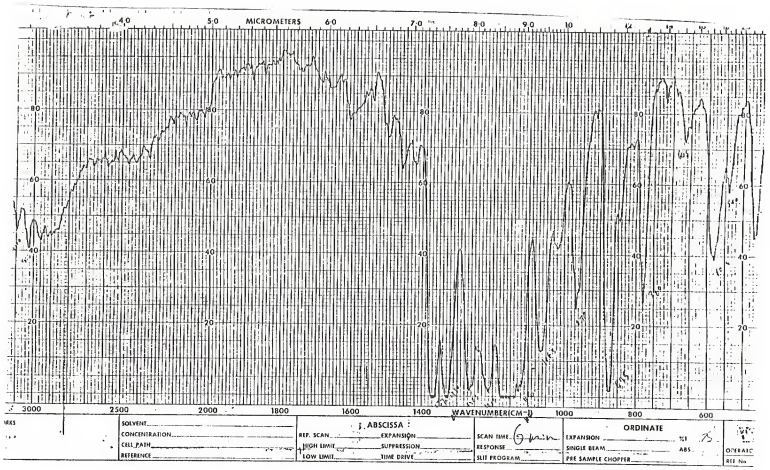


Figure C-8. I. R. Spectrum of 107.

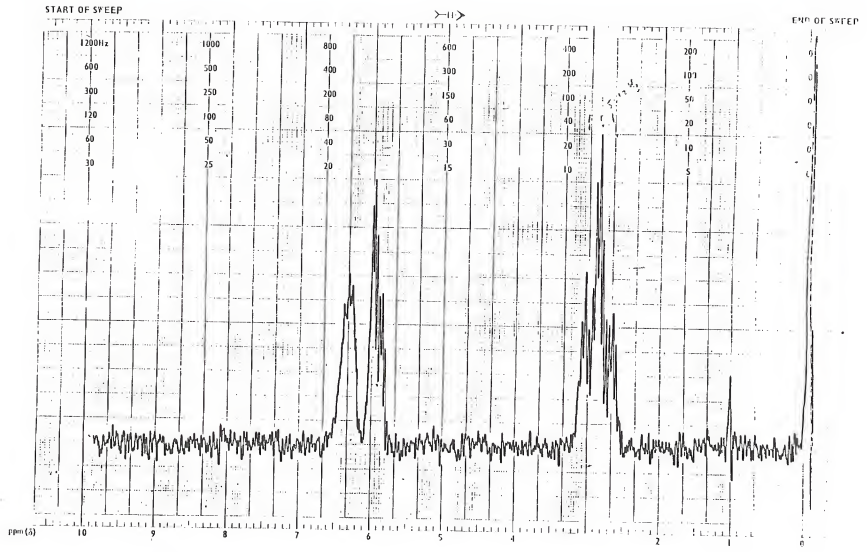


Figure C-9. ^{1}H NMR Spectrum of 108.

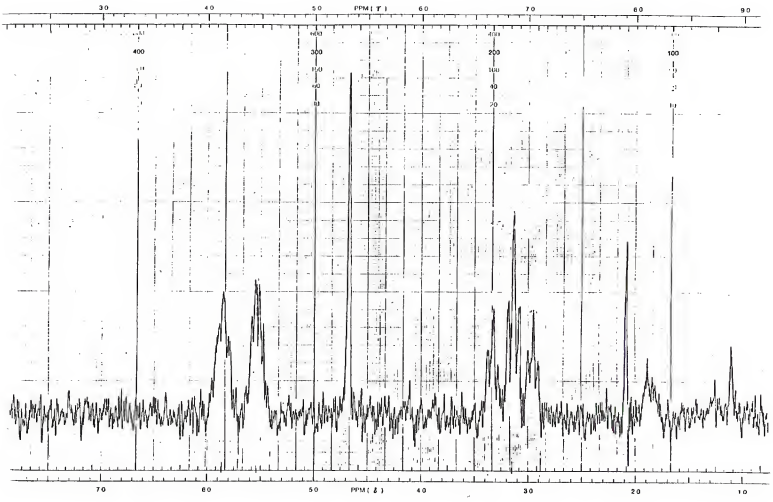


Figure C-10. ^{1}H NMR Spectrum of 109.

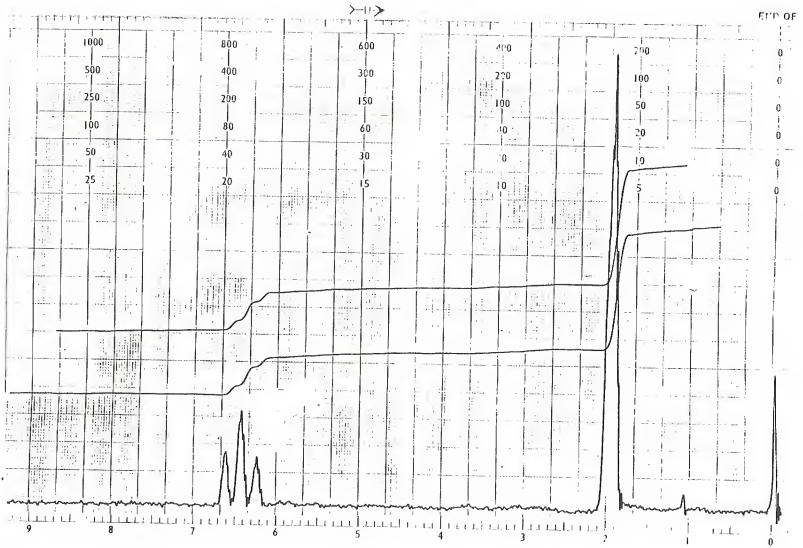


Figure C-11. ^{1}H NMR Spectrum of 110.

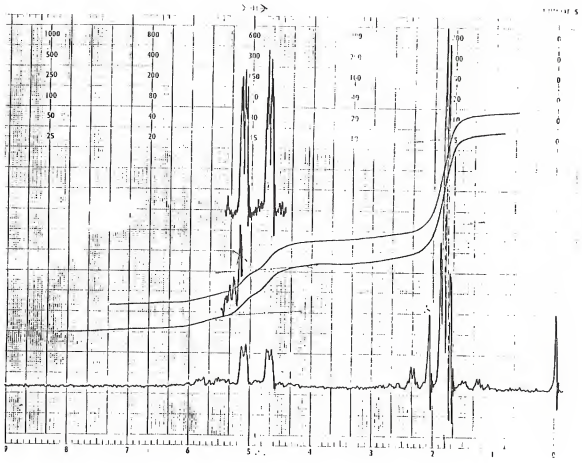


Figure C-12. ^{1}H NMR Spectrum of 111.

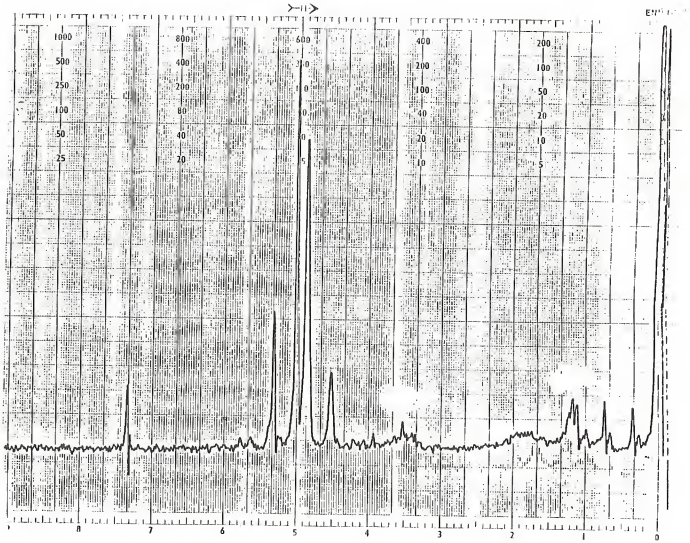


Figure C-13. ^{1}H NMR Spectrum of 106D.

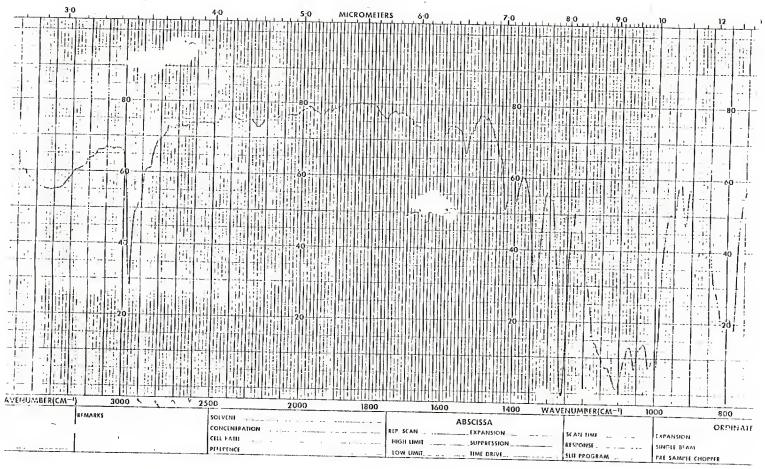


Figure C-14. I. R. Spectrum of 106D.

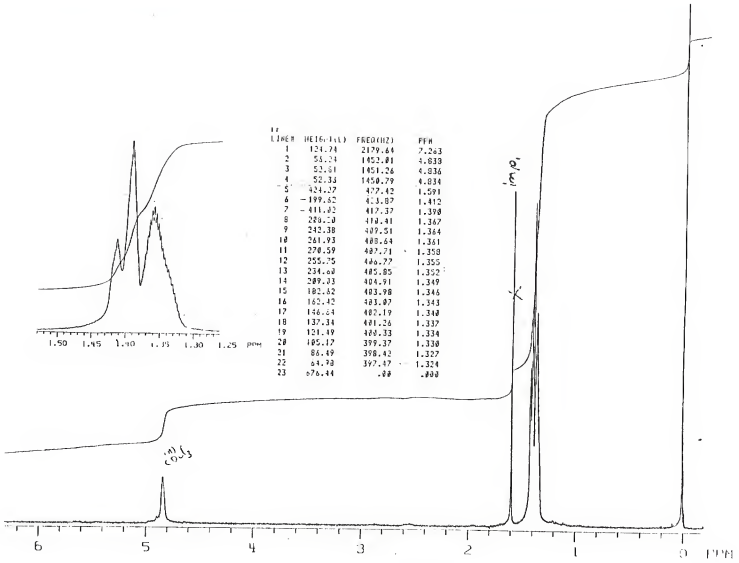


Figure C-15. ^{1}H NMR Spectrum of 107D.

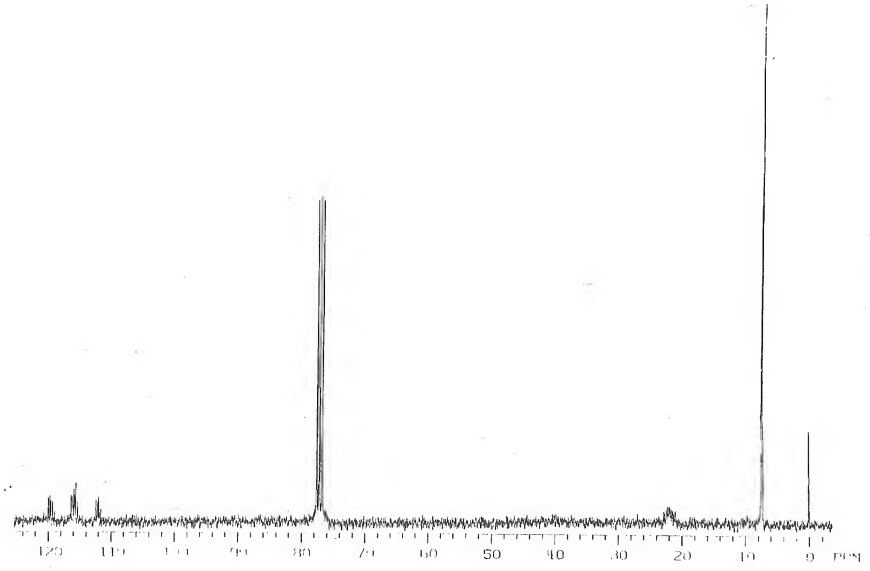


Figure C-16. ^{13}C NMR Spectrum of 107D.

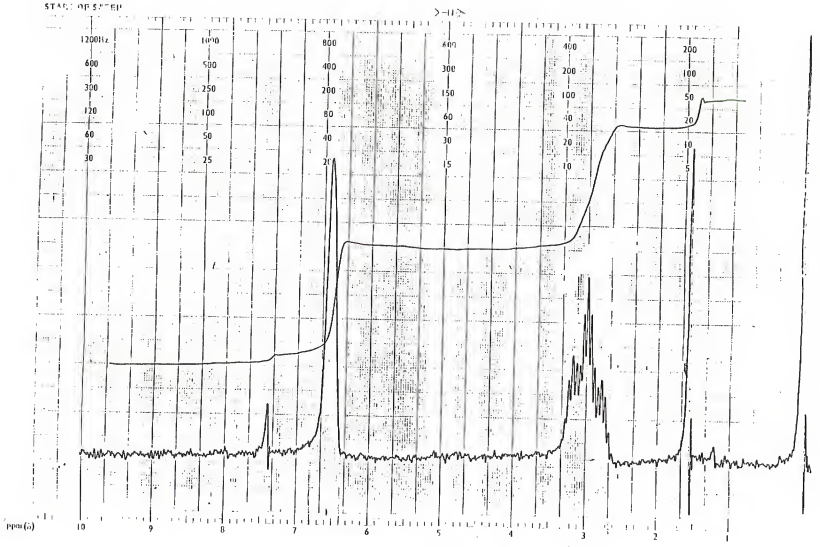


Figure C-17. ^{1}H NMR Spectrum of 108D.

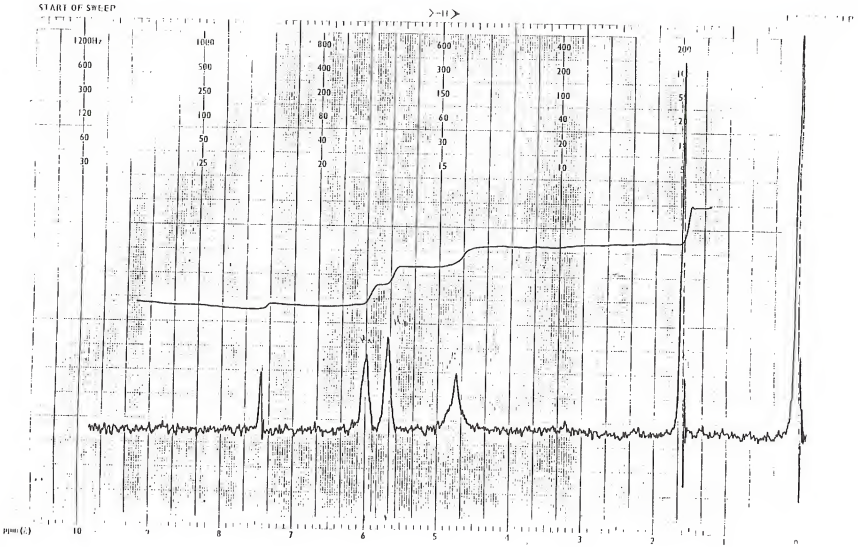


Figure C-18. ^{1}H NMR Spectrum of 109D.

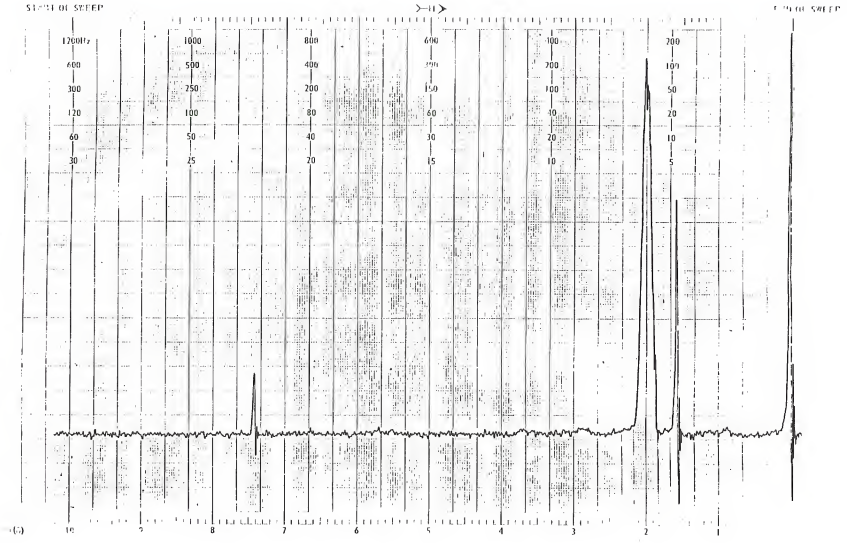


Figure C-19. ^{1}H NMR Spectrum of 110D.

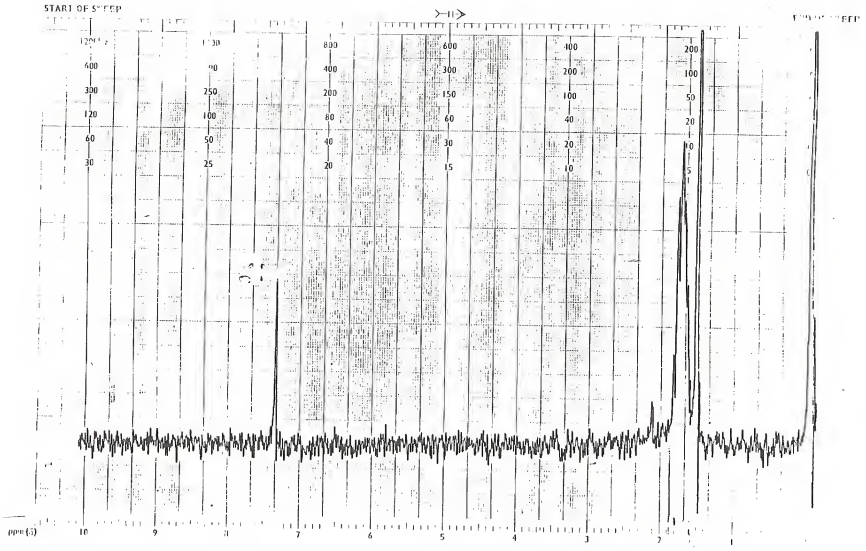


Figure C-20. ^{1}H NMR Spectrum of 111D.

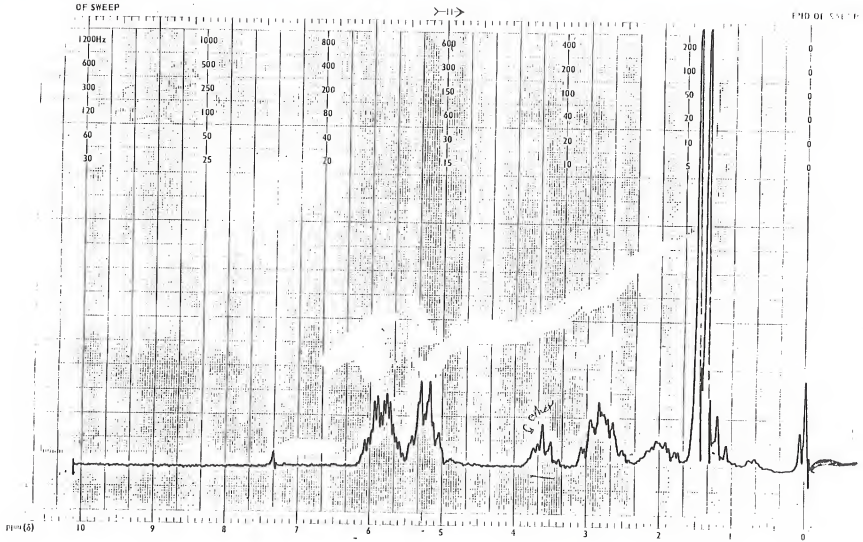


Figure C-21. ^{1}H NMR Spectrum of 119.

Figure C-22. I. R. Spectrum of 119.

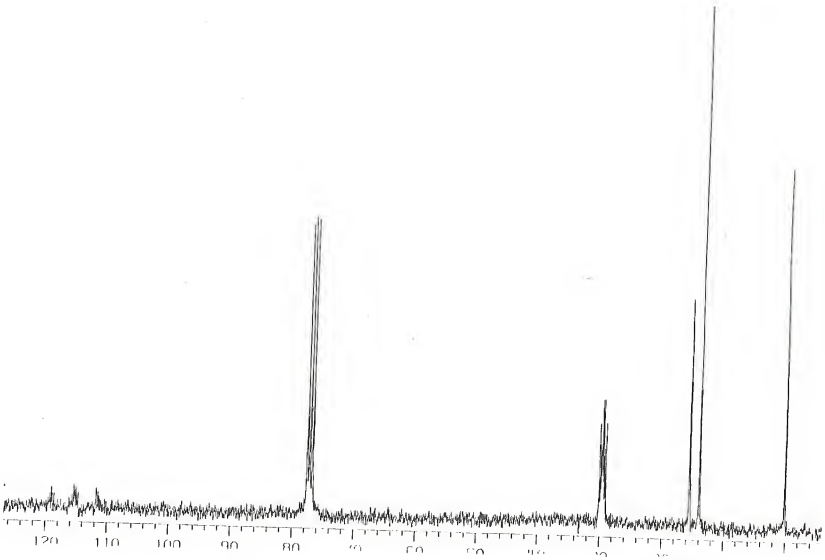


Figure C-23. ^{13}C NMR Spectrum of 120.

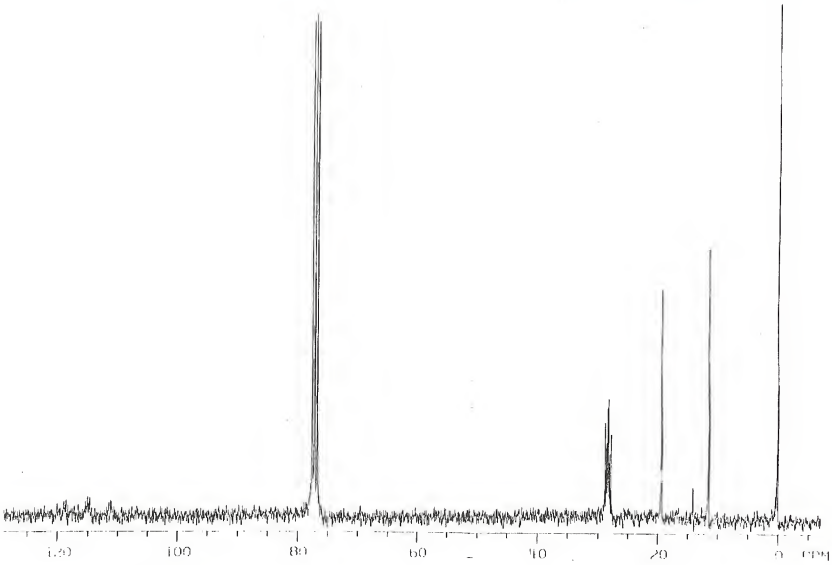


Figure C-24. ^{13}C NMR Spectrum of 121.

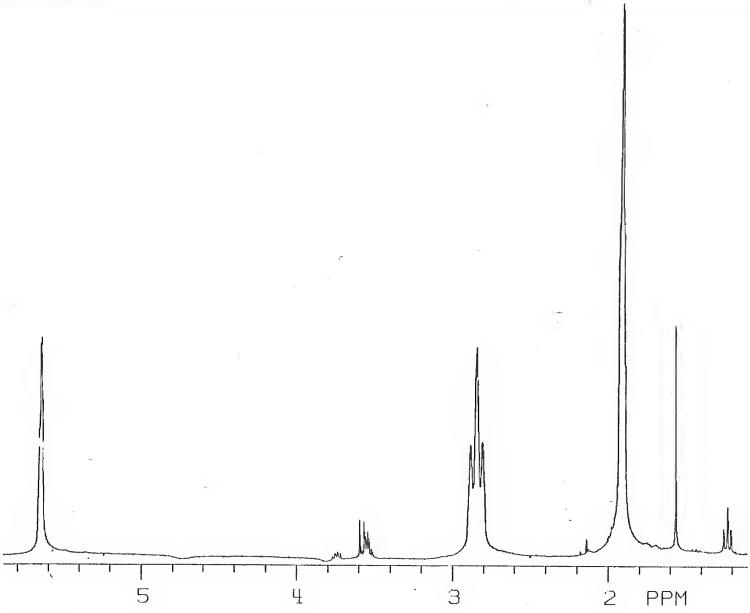


Figure C-25. ^{1}H NMR Spectrum of 122.

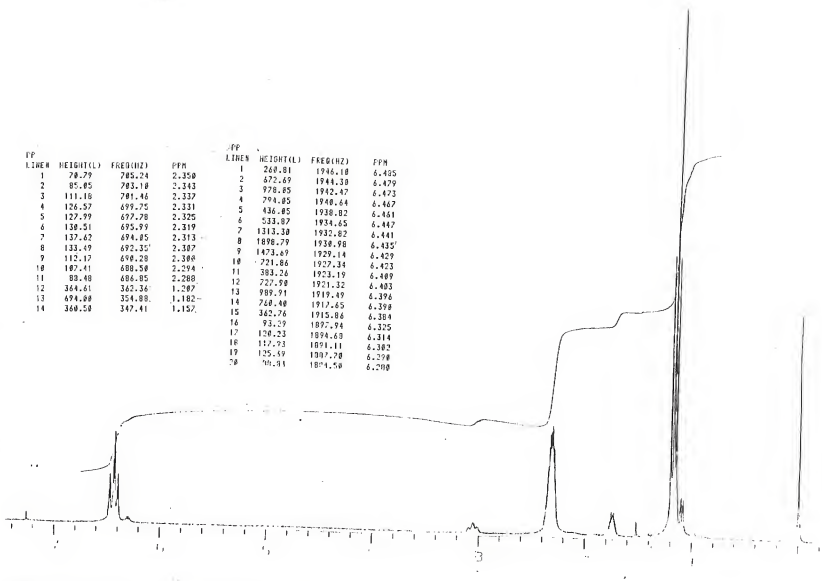


Figure C-26. ^{1}H NMR Spectrum of 123.

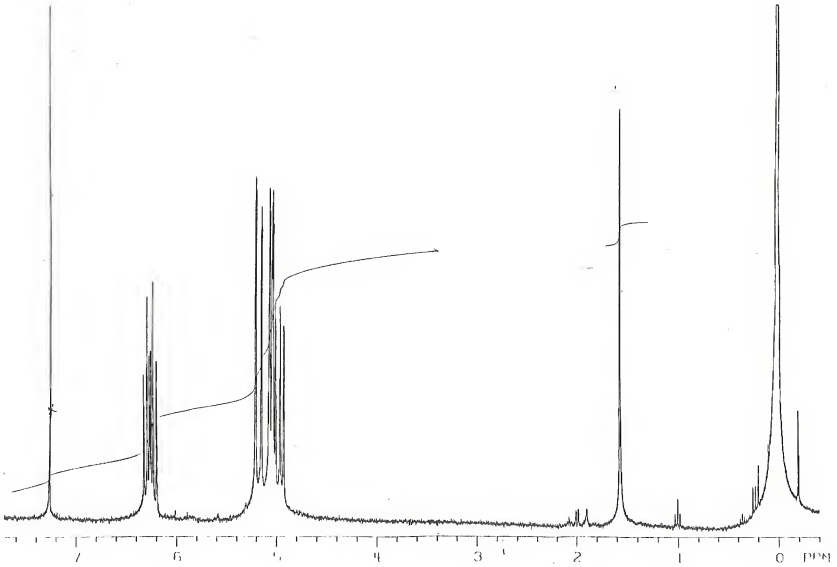


Figure C-27. ^{1}H NMR Spectrum of 138.

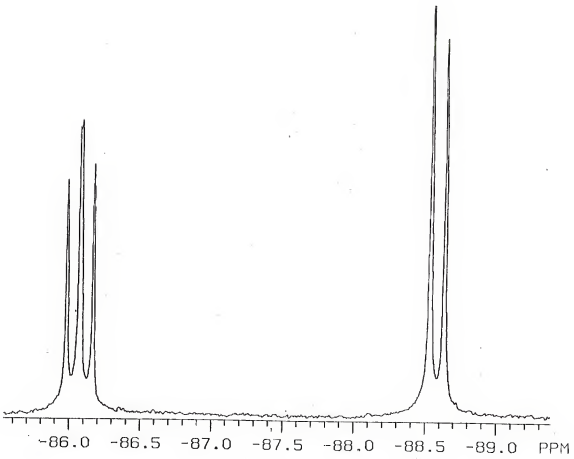


Figure C-28. ^{19}F NMR Spectrum of 138.

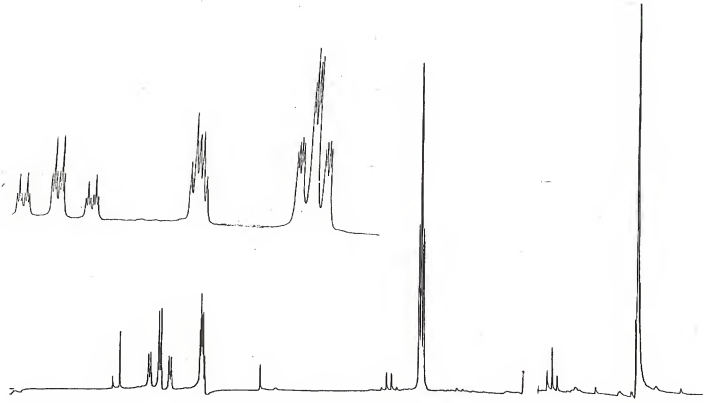


Figure C-29. ^{1}H NMR Spectrum of 139.

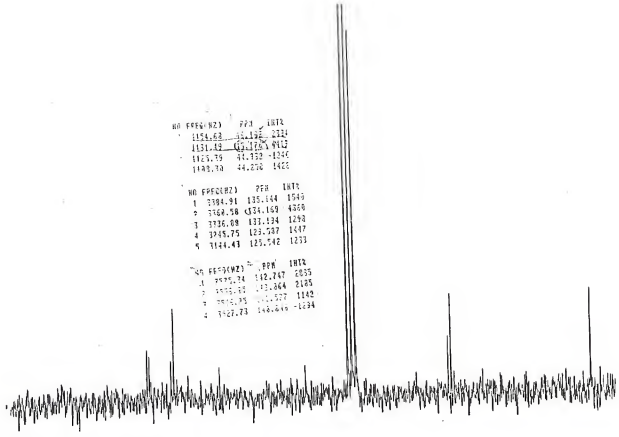


Figure C-30. ^{13}C NMR Spectrum of 139.

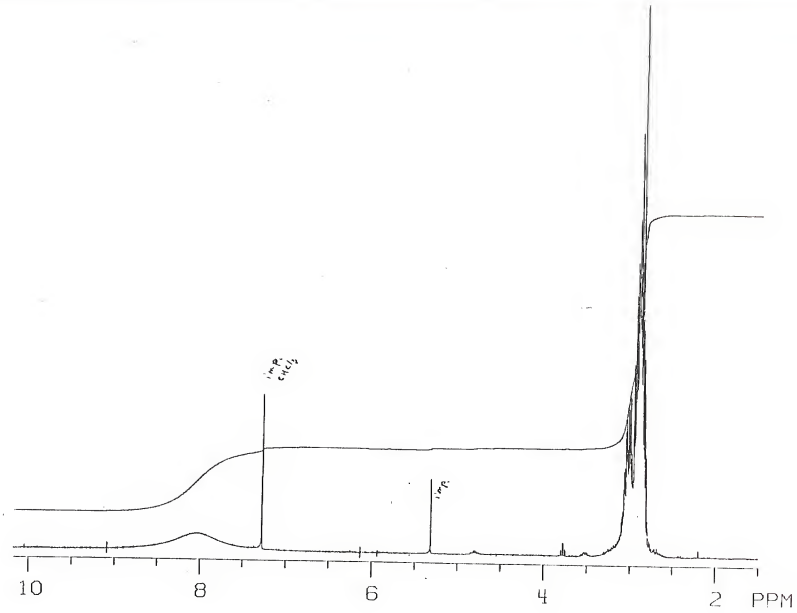


Figure C-31. ^{1}H NMR Spectrum of 144.

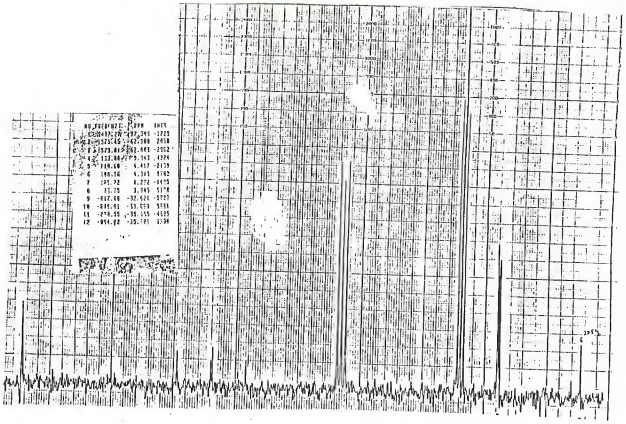


Figure C-32. ^{13}C NMR Spectrum of 144.

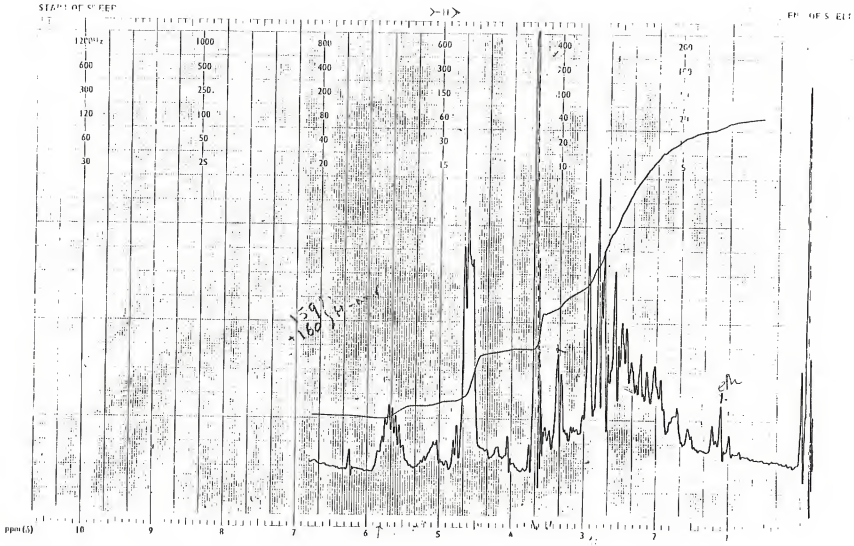


Figure C-33. ^{1}H NMR Spectrum of 159 and 160.

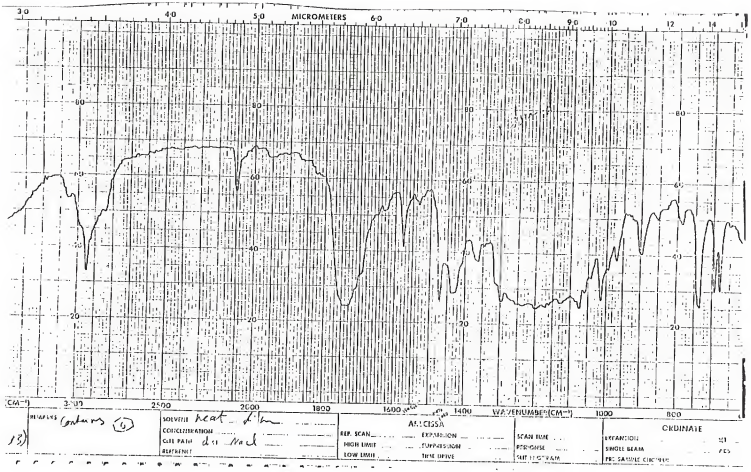


Figure C-34. I. R. Spectrum of 159 and 160.

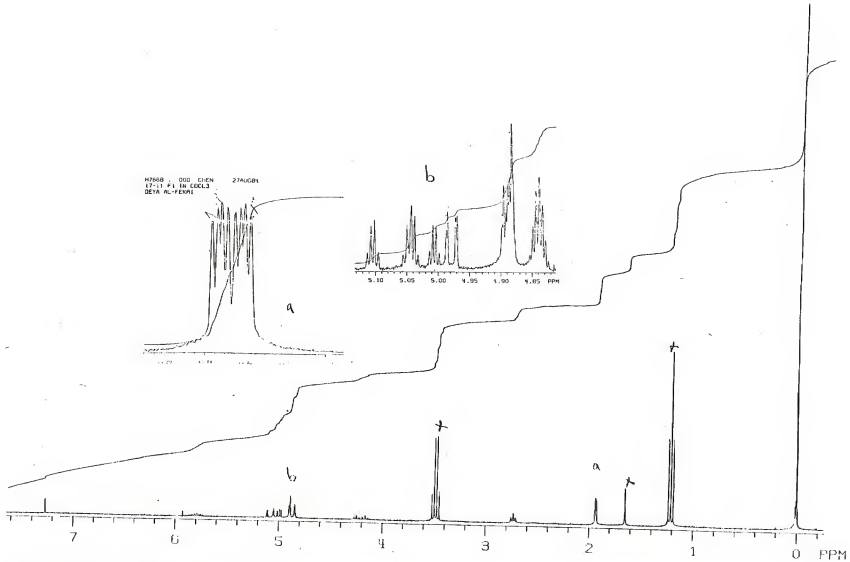


Figure C-35. ^{1}H NMR Spectrum of 161 and 162.

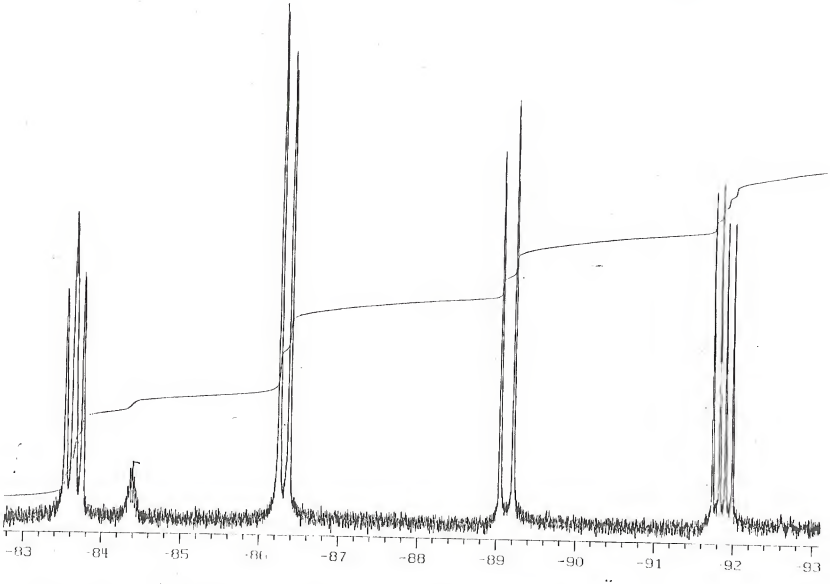


Figure C-36. ^{19}F NMR Spectrum of 161 and 162. (Expansion)

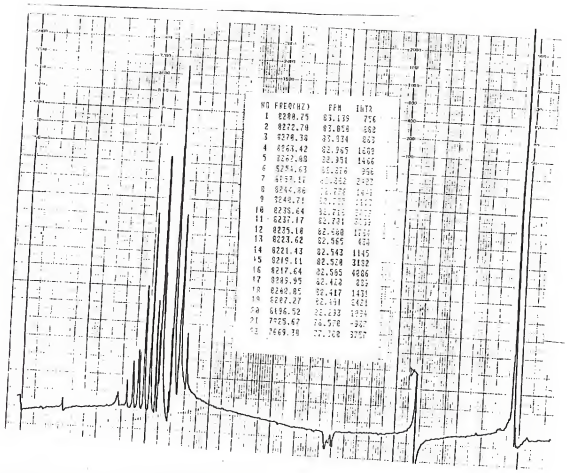


Figure C-37. ^{1}H NMR Spectrum of 163.

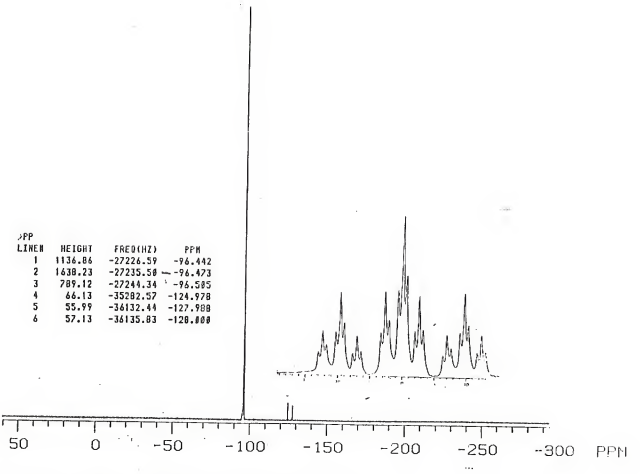


Figure C-38. ^{19}F NMR Spectrum of 163.

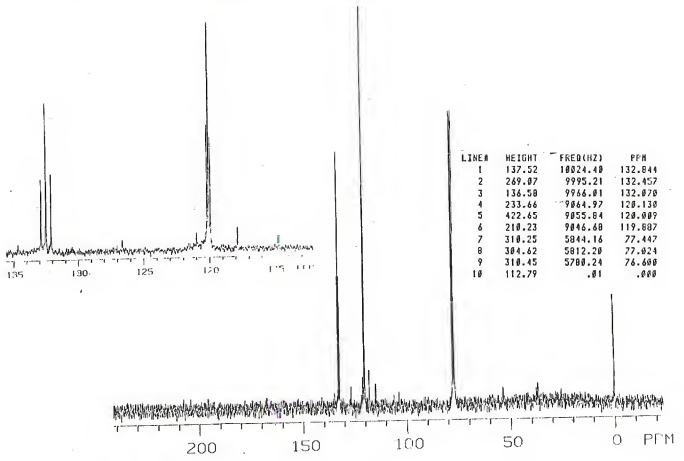


Figure C-39. ^{13}C NMR Spectrum of 163.

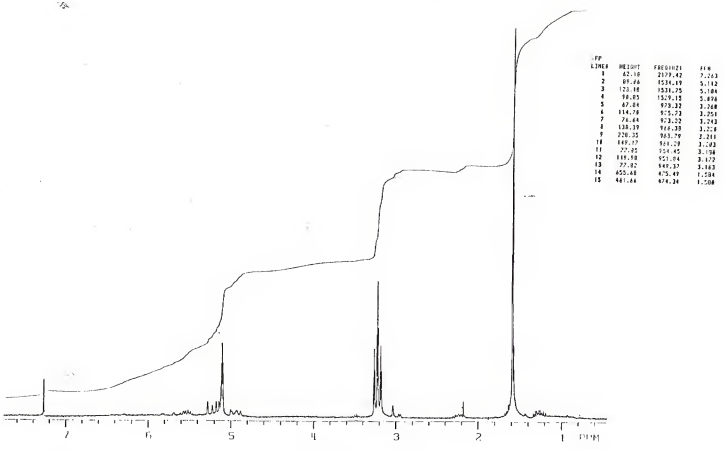


Figure C-40. ^{1}H NMR Spectrum of 164.

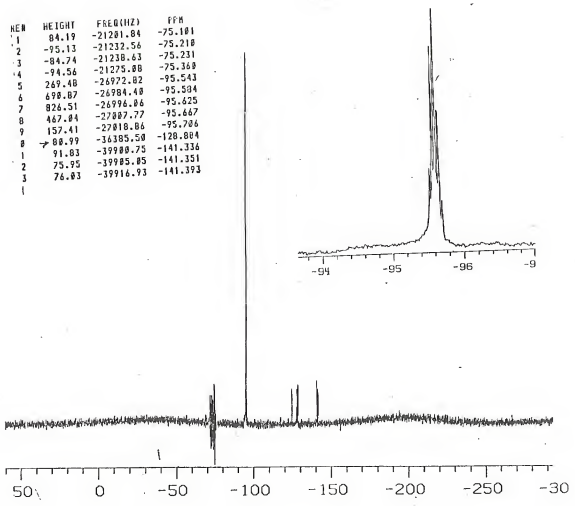


Figure C-41. ^{19}F NMR Spectrum of 164.

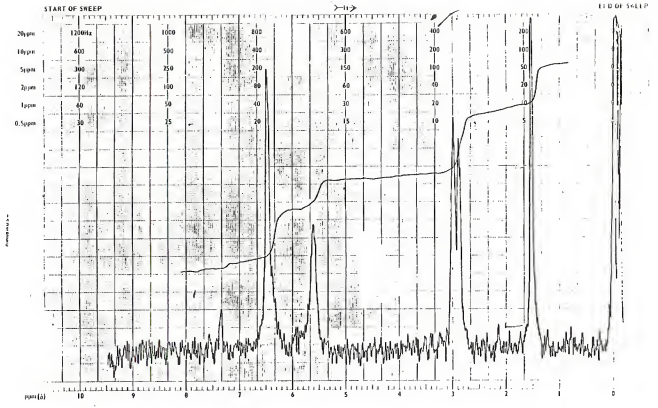


Figure C-42. ^{1}H NMR Spectrum of 167.

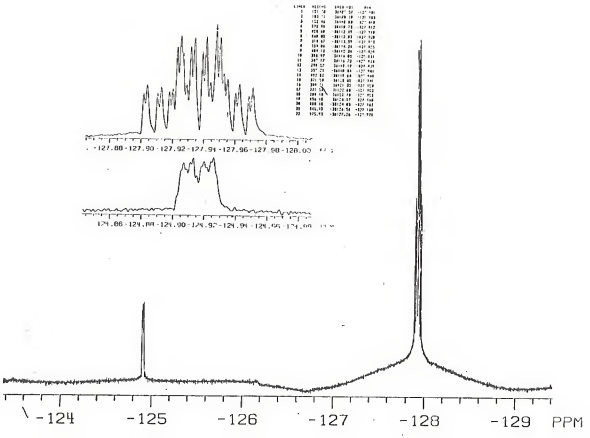


Figure C-43. ^{19}F NMR Spectrum of 167.

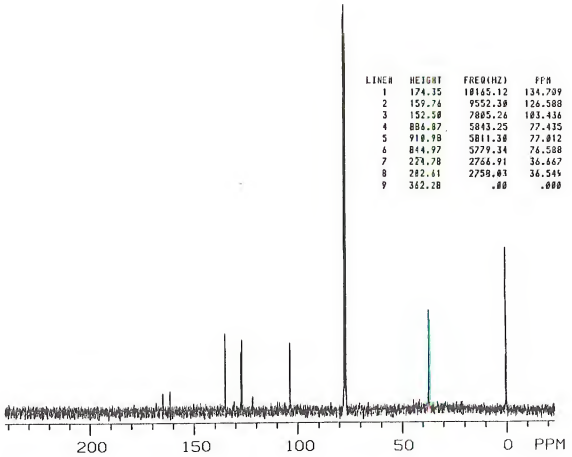


Figure C-44. ^{13}C NMR Spectrum of 167.

REFERENCES

1. a. Chambers, R. D. "Fluorine in Organic Chemistry," John Wiley & Sons, New York, 1973.
   b. Olah, G. A. "Advances in Fluorine Chemistry," 1973, 7, 69.
   c. Pavlath, A. E., and Leffler, A. J. "Aromatic Fluorine Compound", Reinhold Publishing Corporation, New York 1962 p. 30.

2. Schlag, E. W., and Peatman, W. B. J. Am. Chem. Soc. 1964, 86, 1676.

3. Dolbier, W. R., Jr. Acc. Chem. Res. 1981, 14, 195.

4. Hoffmann, R., and Stoher, W. P. J. Am. Chem. Soc. 1971, 93, 6941.

5. O'Neal, H. E., and Benson, S. W. J. Phys. Chem., 1968, 72, 1866.

6. Dolbier, W. R., Jr.; Simon, F. S.; Al-Sader, B. H.; Fiedler, T. H., Jr. J. Am. Chem. Soc. 1981, 103, 717.

7. Elsheimer, S. R., Doctoral Dissertation, University of Florida 1984.

8. Dolbier, W. R., Jr.; Medinger, K. S.; Greenburg, A.; Liebman, J. F. Tetrahedron 1982, 38, 2415.

9. Abell, P. I., and Adolf, P. K. J. Chem. Thermodynamic 1969, 333.

10. Hine, J. "Structural Effects on Equilibria in Organic Chemistry", John Wiley & Sons, New York, 1975, p. 273.

11. Bock, C. W.; George, P.; Mains, G. J.; Trachtman, M. J. Chem. Soc. Perkin Trans. II, 1979, 814.

12. a. Smart, B. E. "Molecular Structure and Energetics", Liebman, J. F., Greenberg, A., Eds. Verlag Chemie International, Inc., Deerfield Beach, in press, Chapter 3: "Fluorinated Organic Molecules".
    b. Kollman, P. J. Am. Chem. Soc., 1974, 96, 4363.

13. Shepperd, W. A. "Organic Fluorine Chemistry", Benjamin, New York, 1969.

14. a. Conlin, R. T., and Frey, H. M. J. Chem. Soc. Faraday Trans.I., 1979, 75, 2556.
    b. idem., ibid. 1980 76, 322.

15. Genaux, C. T.; Kern, F.; Walters, W. D. J. Am. Chem. Soc., 1953, 75, 6196.

16. Daly, D. T., Doctoral Dissertation, University of Florida, 1984.

17. Butler, J. N. J. Am. Chem. Soc., 1962, 84, 1393.

18. a. Cooper, W., and Walters, W. D. J. Am. Chem. Soc., 1958, 80, 4220.
b. Dickens, D.; Frey, H. M.; Metcalfe, J. Trans. Faraday Soc. 1971, 67, 2328.
c. Frey, H. M. Chem. Rev., 1969, 69, 103.

19. Frey, H. M.; Hopkins, R. G.; Vinall, I. C. J. Chem. Soc. Faraday Trans I, 1972, 1874.

20. Chesick, J. P. J. Am. Chem. Soc., 1966, 88, 4800.

21. Criegee, R., and Rimmelin, A. Chem. Ber., 1957, 90, 414.

22. a. Dauben, W. G., and Wiseman, J. R. J. Am. Chem. Soc., 1967, 89, 3545.
b. Chesick, J. P. J. Am. Chem. Soc., 1962, 84, 3250.
c. Wittig, G., and Wingler, F. Chem. Ber., 1964, 97, 2146.

23. Lalonde, R. T. J. Am. Chem. Soc., 1965, 87, 4217.

24. White, D. H.; Condit, P. B.; Bergman, R. G. J. Am. Chem. Soc., 1972, 94, 1348.

25. Doubleday, C., Jr.; McIver, W., Jr.; Page, M. J. Am. Chem. Soc., 1982, 104, 6533.

26. a. Steel, C.; Zand, R.; Hurwitz, P.; Cohen, S. G. J. Am. Chem. Soc., 1964, 86, 679.
b. Halberstadt, M. L., and Chesick, J. P. J. Am. Chem. Soc., 1962, 84, 2688.

27. a. Baldwin, J. E. and Ollerenshaw, J. J. Org. Chem., 1981, 46, 2116, and references cited therein.
b. Wiber, K. B. "Advances in Alicyclic Chemistry," Hart H. and Karabatsos G. J., editors, Academic Press Inc. New York, New York 1968, p. 205.

28. a. Rabinovitch, B. S.; Schlag, E. W.; Wiberg, K. B. J. Chem. Phys., 1958, 28, 504.
b. Schlag, E. W., and Rabinovitch, B. S. J. Am. Chem. Soc., 1960, 82, 5996.

29. a. Buchwalter, S. L., and Closs, G. L. J. Am. Chem. Soc., 1975, 97, 3857.
b. idem., ibid. 1979, 101, 4688.

30. a. Tufariello, J. J.; Bayer, A. C.; Spadaro, J. J., Jr. Tetrahedron Letters, 1972, 363.
b. idem., J. Am. Chem. Soc., 1979, 101, 3309.

31. Wolfgang, R. R., von, and Enderer, K. Ann. Chem., 1969, 730, 82.

32. a. Hoffman, R. Tetrahedron Letters, 1970, 2907.
b. Gunther, H. Tetrahedron Letters, 1970, 5173.
c. Clark, T.; Spitznagel, G. W.; Klose, R.; Schleyer, P. von R. J. Am. Chem. Soc., 1984, 106, 4412.

33. Engel, P. S. Chem. Rev., 1980, 80, 99.

34. McGreer, D. E.; McDaniel, R. S.; Vinje, M. G. Can. J. Chem., 1965, 43, 1389.

35. Van Auken, T. V., and Rinehard, K. L., Jr. J. Am. Chem. Soc., 1962, 84, 3736.

36. Engel, P. S., and Schexnayder, M. A. J. Am. Chem. Soc., 1975, 97, 145.

37. Crawford, R. J., and Mushra, A. J. Am. Chem. Soc., 1966, 88, 3963.

38. Schneider, M. P., and Crawford, R. J. Can. J. Chem., 1970, 48, 628.

39. a. Eaton, D. F.; Bergman, R. G.; Hammond, G. S. J. Am. Chem. Soc., 1972, 94, 1351.
b. Gassman, P. G., and Greenlee, W. J. J. Am. Chem. Soc., 1973, 95, 980.

40. Keppel, R. A., and Bergman, R. G. J. Am. Chem. Soc., 1972, 94, 1350.

41. Frank-Neuman, M. Tetrahedron Letters, 1968, 2979.

42. Kinstle, T. H.; Welch, R. L.; Exley, R. W. J. Am. Chem. Soc., 1967, 89, 3660.

43. a. De Micheli, C.; Gamba-Invernizzi, A.; Gandlfi, R. Tetrahedron Letters, 1975, 2493.
b. Hiberty, P. C., and Ohanessian, G. J. Am. Chem. Soc., 1982, 104, 66.

44. Overberger, C. G.; Weinshenker, N.; Anselme, J-P. J. Am. Chem. Soc., 1965, 87, 4119.

45. Huisgen, R. J. Org. Chem., 1968, 33, 2291.

46. McGeer, D. E.; Chiu, N. W. K.; Vinje, M. G.; Wong, K. C. K. Can. J. Chem., 1965, 43, 1407.

47. a. Crawford, R. J., and Ali, L. H. J. Am. Chem. Soc., 1967, 89, 3908.
b. Gassman, P. G., and Mansfield, K. T. J. Org. Chem., 1967, 32, 915.
c. Criegee R., and Zanker F. Chem. Ber. 98, 1965, 3838.

48. Huisgen, R. Angew. Chem. Int. Ed. Engl., 1963, 2, 633.

49. Atherton, J. H., and Fields, R. J. Chem. Soc. C, 1968, 1507.

50. Barlow, M. G.; Haszeldine, R. N.; Morton, W. D.; Woodward, D. R. J. Chem. Soc. Perkin I, 1973, 1798.

51. Saunier, Y. M.; Danion-Bougot, R., Danion, D.; Carrie, R. Tetrahedron, 1976, 1995.

52. Sustmann, R. Tetrahedron Letters, 1975, 2717.

53. Bryce, M. R.; Chambers, R. D.; Taylor, G. J. Chem. Soc. Perkin I, 1984, 509.

54. Fuller, G., and Tatlow, J. C. J. Chem. Soc., 1961, 3198.

55. White, D. H.; Condit, P. B.; Bergman, R. G. J. Am. Chem. Soc., 1972, 94, 1348.

56. Schlag, E. W.; Rabinovitch, B. S.; Wiberg, K. J. Chem. Phys., 1958, 28, 504.

57. Misani, F.; Speers, L.; Lyon, A. M. J. Am. Chem. Soc. 1956, 78, 2801.

58. Roth, v. W. R., and Martin, M. Ann. Chem., 1966, 702, 1.

59. O'Neal, H. E., and Benson, S. W. Inter. J. Chem. Kin., 1970, 2, 423.

60. a. Norman, R. O.C., on behalf of the Chemical Society "Essays on Free-Radical Chemistry", s.p. 24, Burlington, 1970.

b. Nonbeal, D. C., and Walton, J. C. "Free Radical Chemistry, Structure and Mechanism", Cambridge, 1974, p. 101.

61. Cadogan, J. I. G., and Hey, D. H. Quarterly Reviews, 1954, 8, 308.

62. a. Aston, D. S., and Tedder, J. M. J. Chem. Soc. B, 1970, 1031.
b. Idem, ibid, 1971, 1719.
c. Placzek, D. W., and Rabinovitch, B. S. J. Phys. Chem., 1965, 69, 2141.

63. Baldwin, J. E.; Andrist,A. H.; Pinschmidt, R. K., Jr. Acc. Chem. Res., 1972, 5, 402.

64. Ravishankara, A. R., and Hanrahan, R. J. J. Phys. Chem., 1975, 79, 876.

65. Frey, H. M., and Smith, R. C. Trans. Faraday Soc., 1962, 58, 697.

66. Flowers, M. C., and Frey, H. M. J. Chem. Soc., 1961, 3547.

67. Walborsky, H. M. J. Am. Chem. Soc., 1949, 71, 2941.

68. Sieja, J. B. J. Am. Chem. Soc., 1971, 93, 2481.

69. a. Henne, A. L., and Ruh, R. P. J. Am. Chem. Soc., 1947, 69, 279.
b. Bartlett, P. D.; Montgomery, L. K.; Siedel, B. J. Am. Chem. Soc., 1964, 86, 616.

70. a. Lambert, J. B., and Roberts, J. D. J. Am. Chem. Soc., 1965, 87, 3884.
b. Manatt, S. L.; Vogel, M.; Knutson, D.; Roberts, J. D. J. Am. Chem. Soc., 1964, 86, 2645.
c. Burch, G. N. B., Doctoral Dissertation, Ohio State University, 1949.
d. Raasch, M. S.; Miegel, R. E.; Castle, J. E. J. Am. Chem. Soc., 1959, 81, 2678.
e. Bellus, v. D.; Fischer, H.; Greuter, H.; Martin, P. Helv. Chem. Acta, 1978, 61, 1784.

71. Srinivasan, R. J. Am. Chem. Soc., 1963, 85, 4045.

72. Tarrant, P., and Lovelace, A. M. J. Am. Chem. Soc., 1954, 76, 3466.

73. Fuson, R. C., and Rabjohn, N. Organic Syntheses Collective Volume III, John Wiley & Sons, Inc., New York, 1955, pp. 557, 591.

74. Weisz, A., and Mandelbaum, A. J. Org. Chem., 1984, 49, 2648.

75. a. Ham, G. E., and Coker, W. P. J. Org. Chem., 1964, 29, 194.

76. a. Bacha, J. D., and Kochi, J. K. Tetrahedron, 1968, 2215.
b. Tobe, Y.; Fukuda, Y., Kakiuchi, K.; Odaira, Y. J. Org. Chem., 1984, 49, 2012.

77. Newmark, R. A.; Apai, G. R.; Michael, R. O. J. Mag. Res., 1969, 1, 418.

78. Kinstle, T. H.; Loo, D.; Beight, D. W., Bowling Green State University, private communication.

79. Phillips, W. D. J. Chem. Phys, 1956, 25, 949.

80. Dolbier, W. R., Jr., and Sellers, S. F. J. Am. Chem. Soc., 1982, 104, 2494.

81. Roth, W.; Kirmse, W.; Hoffman, W. Chem. Ber., 1982, 115, 2508.

82. Baldwin, J. E., and Andrews, G. D. J. Am. Chem. Soc., 1972, 94, 1775.

83. a. Doering, W. v. E., and Roth, W. R. Tetrahedron, 1963, 19, 715, p. 229.
b. Furukawa, J., Kawabata, N.; Nishimura, J. Tetrahedron, 1968, 24, 53.
c. Takaya, H.; Suzuki, T.; kumagai, Y.; Yamakawa, M.; Noyori, R. J. Org. Chem., 1981, 46, 2846.

84. Cooper, W., and Walter, W. D. J. Am. Chem. Soc., 1958, 80, 4220.

85. Schleyer, P. von R.; Williams, J. E.; Blanchard, K. R. J. Am. Chem. Soc., 1970, 92, 2377.

86. a. Carpenter, B. K. Tetrahedron, 1978, 34, 1877.
b. Frey, H. M. Trans. Faraday Soc., 1962, 58, 957.
c. Frey, H. M.; Pope, B. M.; Skinner, R. F. Trans. Faraday Soc., 1967, 63, 1166.
d. Frey, H. M. ibid. 1963, 59, 1619.
e. Dolbier, W. R., Jr. unpublished results.

87. a. Dickens, D.; Frey, H. M.; Metcalfe, J. Trans. Faraday Soc., 1971, 67, 2328.
b. Criegee, R.; Seebach, D.; Winter, R. E.; Borretzen, B.; Brune, H-A. Chem. Ber., 1965, 98, 2339.

88. a. Kirmse, W.; Rondan, N. G.; Houk, K. N. J. Am. Chem. Soc., 1984, 106, 7989.
b. Dolbier, W. R., Jr.; Koroniak, H.; Burton, D. J.; Bailey, A. R.; Shaw, G. S.; Hansen, S. W. J. Am. Chem. Soc., 1984, 106, 1871.

89. a. Taskinen, E. Tetrahedron, 1976, 32, 2327.
b. Hine, J., and Flachskam, N. W. J. Am. Chem. Soc., 1973, 95, 1179.

90. a. Huang, Y. S., and Beaudet, R. A. J. Molec. Spectr., 1970, 34, 1.
b. Chang, C. H.; Anderson, A. L.; Bauer, S. M. J. Org. Chem., 1971, 36, 920.
c. Lide, D. R., Jr. J. Chem. Phys., 1962, 37, 2074.
d. Beaudet, R. A. ibid. 1965, 42, 3758.
e. Huckerby, T. N.; Mooney, E. F.; Stephens, R. Tetrahedron, 1967, 23, 709.
f. Miller, F. A.; Elbert, W. F.; Pingitore, W. J. Mol. Structure, 1977, 41, 19.
g. Wurrey, C. J.; Bucy, W.E.; Durig, J. R. J. Chem. Phys., 1977, 67, 2765.

91. a. Bothner-By, A. A., and Jung, D. J. Am. Chem. Soc., 1968, 90, 2342.
b. Brundle, C. R.; Robin, M. B.; Kuebler, N. A.; Basch, H. J. Am. Chem. Soc., 1972, 94, 1451.
c. Conrad, R. M., and Dows, D. A. Spectrochimica Acta, 1965, 21, 1039.

92. a. Forster, H., and Vogtle, F. Angew. Chem. Int. Ed. Engl., 1977, 16, 429.
b. Mallory, F. B.; Mallory, C. W.; Fedarka M-C. J. Am. Chem. Soc., 1974, 96, 3536.

93. a. De Boer, TH. J., and Backer, H. J. "Organic Syntheses Collective Volume IV," John Wiley & Sons, Inc., New York, 1943, p. 250, 943.
b. Fieser, L., and Fieser, M. "Reagents for Organic Synthesis," John Wiley & Sons, Inc., New York, 1967, p. 191.

94. a. Lane, C. F., and Kramer, G. W. Aldrichimica Acta, 1977, 10, 11.
b. Noller, C. R. "Organic Syntheses Collective Volume II", Blatt, A. H., Ed., John Wiley & Sons, Inc., New York, 1943, p. 184.

95. Taylor, D. R. Tetrahedron Letters, 1967, 3277.

96. Benson, S. W. "Thermochemical Kinetics," 2nd. Ed., John Wiley & Sons, Inc., New York, 1976.

BIOGRAPHICAL SKETCH

Dheya Al-Fekri was born in Najaf, Iraq, the city having the giant golden dome with the twin Minaretes. When he was two months old, his family moved to Baghdad, Iraq, where he was educated until his graduation from high school in 1970.

When he was seven years old, he admired a toy called a car. He still enjoys driving, repairing, and reading about that toy.

In 1974 he received his B.S. degree in industrial chemistry from the University of Baghdad. Three years later he graduated with his M.S. degree from the same University.

Although Dheya was fascinated when his father generously rewarded him with what he admired during his childhood, his ambitions were not fulfilled until he joined the graduate program in the Chemistry Department at the University of Florida in 1979 and then worked for Professor William R. Dolbier, Jr., for the past four years.

Dheya presented part of his research work at the Florida meeting of the American Chemical Society (1983). He is a co-author of four papers that have been published in journals such as Journal of the American Chemical Society, Journal of Organic Chemistry, and Tetrahedron Letters.

Upon graduation from the University of Florida, Dheya will go to work as a Research and Development Chemist at Jackson Laboratory, E. I. Du Pont De Nemours & Co., Inc., Deepwater, New Jersey.

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

William R. Dolbier, Jr.
Chairman
Professor of Chemistry

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

William M. Jones
Professor of Chemistry

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Merle A. Battiste
Professor of Chemistry

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Timothy J. Anderson
Associate Professor of
Chemical Engineering

I certify that I have read this study and that in my opinion it conforms to acceptable standards of scholarly presentation and is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Russell S. Drago
Professor of Chemistry

This dissertation was submitted to the Graduate Faculty of the Department of Chemistry in the College of Liberal Arts and Sciences and to the Graduate Council, and was accepted as partial fulfillment of the requirements for the degree of Doctor of Philosophy.

January 1985

Dean for Graduate Studies
and Research